TABLE Explainer

Meat, metrics and mindsets:

Exploring debates on the role of livestock and alternatives in diets and farming

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Introduction

Should we eat meat, eggs, dairy and other animal-sourced foods? If so, how should we produce them and how much should we eat? If not, what should we eat instead? These are just some of the more contentious debates about the future of food systems.

This Explainer summarises some of the key debates about livestock and its alternatives and describes both the arguments and the evidence underpinning different points of view. We look both at foodstuffs (meat, fish, plants and new foods based on cells grown in bioreactors) and farming methods (both intensive and extensive) with regards to discussions about their environmental, health and social impacts. In so doing, we explore the assumptions and values that often lead stakeholders to differing conclusions about what a sustainable food system looks like.

Meat

Debates about meat (and other animal-sourced foods such as milk and eggs) in general centre on how much, if any, we should eat and how it should be produced. These debates cover several environmental, health and social concerns, including climate impacts, feed-food competition, nutrient provision, labour conditions, rural livelihoods and animal welfare.

Livestock farming systems can be differentiated according to whether they are more extensive (generally lower yielding and hence using a lot of land, for example entirely pasture-fed) or more **intensive** (such as enclosed feedlots); whether the animals raised are **ruminants** (e.g. cattle, sheep) or **monogastrics** (e.g. poultry, pigs); and whether livestock are fed mostly on human-edible feed such as grains or soy, or mostly on human-inedible feed such as grass or by-products from industry or food processing. Note that these divisions are rarely clear cut: for example, a grazing system with high inputs of fertilisers and feed supplements might be regarded as intensive in comparison to grazing systems with fewer external inputs, but extensive in comparison to enclosed feedlots[1]. Advocates of livestock farming make various arguments about the merits and drawbacks of each type of production. Meanwhile, others argue that we should reduce or even eliminate livestock consumption and production, and produce and consume more plant-based foods instead (discussed later). There is some overlap between positions that advocate some positive role for livestock and positions that call for a reduction in animal-sourced food production.

Environmental issues around meat

There are many environmental concerns around the production of meat and other livestock products, such as ammonia emissions from intensively housed livestock, overgrazing, manure run-off leading to eutrophication, and the impacts of the pesticides, fertilisers and other resources that are used to produce livestock feed. That said, the nature and extent of livestock's impacts vary widely according to the species and production system. This section focuses on three particularly contested issues: how to measure livestock's climate impact; the implications of the source of the animal feed; and the impacts that different types of land use have on nature and on soil and biomass carbon stocks.

The climate impact of meat and other foods can be understood in several ways. Conventional carbon footprints assess climate impact using the metric of **Global Warming Potential**, which can be applied over different timeframes, most commonly 100 years (GWP_{100}). A newer metric **GWP*** is designed to emphasise the unique characteristics of short-lived greenhouse gases that break down rapidly in the atmosphere, most notably methane.

1 Garnett, T., Godde, C., Muller, A., Röös, E., Smith, P., De Boer, I.J.M., zu Ermgassen, E., Herrero, M., Van Middelaar, C.E., Schader, C. and Van Zanten, H.H.E. (2017), Grazed and confused? Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question-and what it all means for greenhouse gas emissions. Food Climate Research Network. PDF available here.

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Furthermore, a variety of processes can be included within or excluded from the boundaries that are defined when calculating a food's carbon footprint, such as soil carbon sequestration and forgone sequestration in native biomass, affecting the results. Figure 1 below illustrates how each of these three approaches can be interpreted differently and each topic is discussed in more detail over the next few paragraphs.

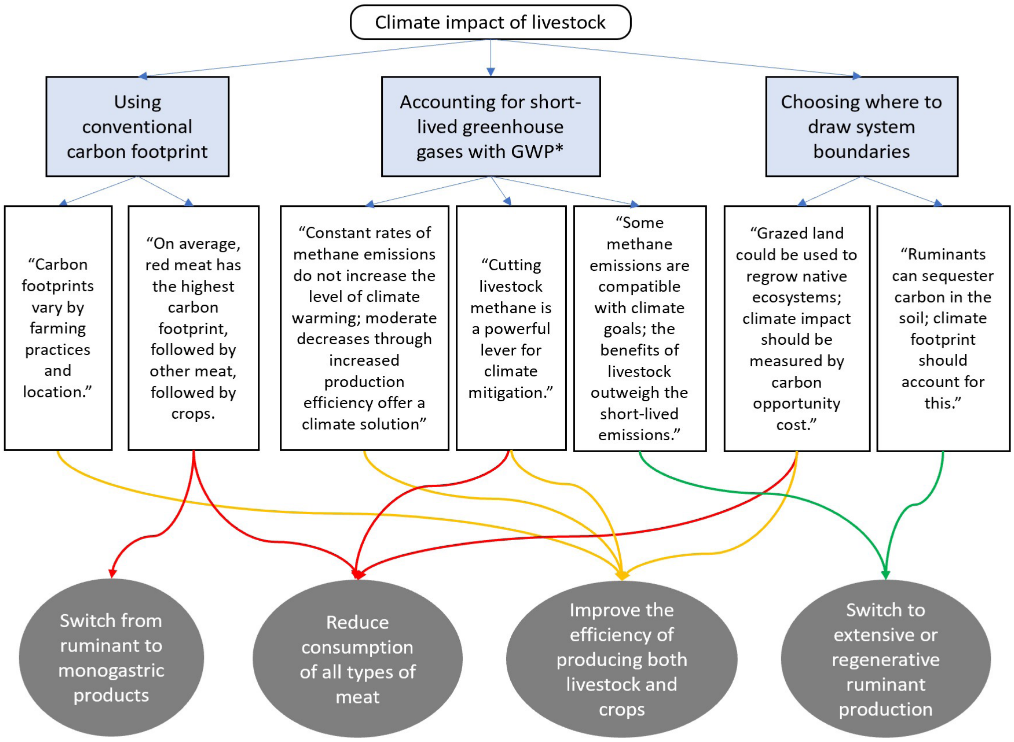

Figure 1: Three approaches to measuring the climate impacts of livestock, and how they can be interpreted differently by different stakeholders to reach a range of conclusions. Graphic produced by TABLE.

As shown in Figure 2, a 2018 global review[2] by Poore and Nemecek found that, per gram of protein, beef from beef herds has the highest average carbon footprint[3] of all the food categories studied, followed by lamb & mutton and beef from dairy herds – many times greater than plant-sourced foods such as tofu, nuts and peas, with other meats including poultry and pork having an intermediate footprint. This pattern of relative impacts is often used to support the argument for dietary shift either from ruminant products to monogastric products, or from livestock products as a whole to plant-based foods.

The high carbon footprint of ruminants relative to monogastrics is partly due to the methane that ruminants produce – a side effect of their ability to digest grass and hence turn human-inedible feeds into food, although many ruminants are in fact fed human-edible feed as at least part of their diet[4]. However, a similar pattern is seen even if only non-methane greenhouse gases (mostly carbon dioxide and nitrous oxide) are considered: on average across the globe, ruminant meat has the highest non-methane emissions per gram of protein, followed by other animal-sourced protein-rich foods (e.g. poultry meat), followed by plant-sourced proteins (e.g. tofu; see the solid portion of the bars in Figure 2).

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2 Poore, J. and Nemecek, T. (2018), Reducing food's environmental impacts through producers and consumers. Science, 360(6392), pp.987-992.

3 These carbon footprints are calculated from farm inputs to the point of retail using GWP_{100}, and do not include carbon opportunity costs – discussed further below – which account for the carbon that could be captured by restoring native biomass (e.g. forest) on land that is currently farmed.

4 Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C. and Gerber, P. (2017), Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Global Food Security, 14, pp.1-8.

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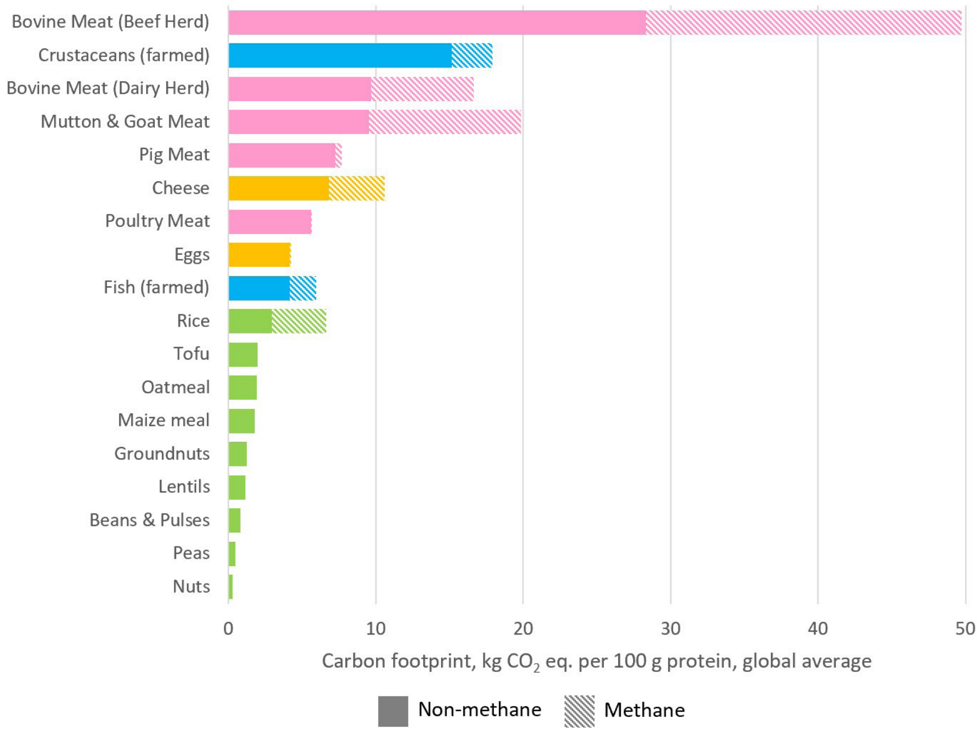

Figure 2: Global mean carbon footprint of various protein-rich foods, given in kg CO_2 eq. per 100g of protein, using GWP_{100}. Pink bars indicate meat; blue, seafood; orange, other animal products; green, crops. The hatched portions of the bars represent the methane component of the carbon footprint (in terms of kg CO_2 eq.) and the solid portions represent all other greenhouse gases (including carbon dioxide and nitrous oxide, in terms of kg CO_2 eq.). Foods are displayed in order of the non-methane component of their carbon footprint. Note that the figures shown are global averages across all types of management practices; there is significant variation within each category, not illustrated in this graph. Data source: Poore and Nemecek (2018) with additional data provided directly by Joseph Poore, and protein content data from the FAO's Food Composition Tables. Figure produced by TABLE, based on a similar graph by Our World in Data.

Another important result of the paper is that there is a wide range in the impacts of each type of food, depending on management practices, location and so on – Figure 2 shows only *global average* impacts. For example, the carbon footprint of beef from beef herds ranges from 19 kg CO_2 eq. per 100 g protein (in the 5th percentile of impacts) to 135 kg CO_2 eq. per 100 g protein (in the 95th percentile)[5]. As a result, some reductions in impact could be made either by adopting new farm management practices[6] or by prioritising the production of crops and livestock in the regions and conditions where they have the lowest impacts, relative to production of the same food elsewhere with higher impacts.

Different stakeholders use this line of argument to advocate for a range of solutions. On the one hand, those coming from an **ecomodernist** perspective, for example, sometimes argue that feedlot beef has lower greenhouse gas emissions (and land use and nutrient emissions) than grass-fed beef. On the other hand, advocates for extensive or organic ruminant grazing argue that some farms can achieve significant soil carbon sequestration by using certain grazing management strategies (partially balancing the methane and other greenhouse gas emissions produced by ruminants – this issue is discussed further below), as well as lower non-methane emissions (nitrous oxide and carbon

5 Supplementary Data S2 of Poore and Nemecek.

6 See Figure S6 in the supplementary material of Poore and Nemecek, and the section "Set and incentivize mitigation targets" of the main text of the paper.

dioxide) than conventional farms[7]. Another argument commonly made is that if there is to be some level of ruminant meat production, it should be from regions that offer the lowest production impacts. For example, beef produced in the UK has a 43% lower average carbon footprint than beef produced in Brazil[8]. Some proponents of livestock production argue that carbon footprints should be based not only on mass of food or total protein content, but on various indices that incorporate a range of macro- or micronutrients. For example, one study finds that when the essential amino acid profile of foods is accounted for, the apparent carbon footprints of several animal-sourced foods and also tofu appear more favourable compared to carbon footprints based on total protein content, because of the high protein quality of those foods. Nevertheless, even according to this study's approach, the carbon footprints of all four plant-based foods it considers remain lower than those of all four animal-sourced foods. Furthermore, the study does not account for the potentially better amino acid profile that could be achieved by combining multiple plant sources of protein[9].

The measurement of methane's climate impacts is complicated by its behaviour in the atmosphere. Methane has an average atmospheric lifetime of 11.8 years because it breaks down rapidly into carbon dioxide and water, whereas carbon dioxide, being a relatively stable molecule, can remain in the atmosphere for centuries. The conventional **Global Warming Potential** measure of carbon footprint is typically applied over a fixed time period. The commonly used 100-year timeframe (GWP_{100}) shows that over one century, methane from biological sources has 27 times the warming impact of CO_2. Conventional GWP can also be applied over a shorter timeframe: GWP_{20} shows that methane has 80 times the warming effect of CO_2 when measured over 20 years[10].

An alternative metric, GWP*, offers a different way of understanding the warming effect of short-lived greenhouse gases. GWP* emphasises that what determines methane's contribution to climate warming is not the cumulative total (as for long-lived CO_2); rather, it is the current rate of methane emissions and whether that rate is increasing or declining in comparison to historical methane emissions.

According to GWP*, a constant, established source of methane emissions only continues to increase the temperature slightly. The decline of a source of methane at a rate of more than 3% per decade acts to reduce global temperatures, with the cooling effects being felt within a couple of decades. A source of methane that is increasing has a rapid and large warming effect on the climate[11].

Interpretations of what the results of GWP* mean for the broader food system differ depending on assumptions and values about wider environmental and social issues. Since GWP* underlines that ongoing methane emissions from farmed animals that decline at only 3% per decade are compatible with stable temperatures, livestock advocates often use this observation to argue that some ongoing slowly decreasing level of methane emissions from ruminant production is compatible with climate mitigation goals. This viewpoint tends to see current livestock

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7 See Table 2 of Lynch, J., Garnett, T., Persson, M., Röös, E. and Reisinger, A. (2020), Methane and the sustainability of ruminant livestock. University of Oxford: Food Climate Research Network. It has also been found in one paper that emissions of nitrous oxide from pastures containing white clover may have been overestimated by the Intergovernmental Panel on Climate Change – see Rothamsted Research, Grazing experiment shows IPCC's own estimates of climate impacts are off, which summarises McAuliffe, G.A., López-Aizpún, M., Blackwell, M.S.A., Castellano-Hinojosa, A., Darch, T., Evans, J., Horrocks, C., Le Cocq, K., Takahashi, T., Harris, P. and Lee, M.R.F. (2020), Elucidating three-way interactions between soil, pasture and animals that regulate nitrous oxide emissions from temperate grazing systems. *Agriculture, ecosystems & environment*, 300, p.106978.

8 See the TABLE blog Fletcher, E. (2020), Why the beef with UK livestock? The need to distinguish between local and global scales in discussions on food sustainability.

9 McAuliffe, G.A., Takahashi, T., Beal, T., Huppertz, T., Leroy, F., Buttriss, J., Collins, A.L., Drewnowski, A., McLaren, S.J., Ortenzi, F. and van der Pols, J.C. (2022), Protein quality as a complementary functional unit in life cycle assessment (LCA). *The International Journal of Life Cycle Assessment*, pp.1-10 (TABLE summary).

10 When measured according to conventional Global Warming Potential (GWP), methane from biological sources has 27 times the climate warming effect of CO_2 over 100 years, or 80 times the warming effect over 20 years. GWP and atmospheric lifetimes figures for non-fossil methane taken from Table 7.15 of the IPCC's AR6 report, Chapter 7.

11 See Oxford Martin Programme on Climate Pollutants (2022), Climate Metrics for Ruminant Livestock; and Lynch, J., Cain, M., Pierrehumbert, R. and Allen, M. (2020), Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short-and long-lived climate pollutants. *Environmental Research Letters*, 15(4), p.044023 (TABLE summary).

methane emissions as a baseline that should be regarded as (almost) climatically neutral, because livestock will only induce higher temperatures if their rate of methane emissions either increases or falls at less than 3% per decade. Any gradual reductions of *more* than 3% per decade, such as through using feed additives that reduce methane production, are hence seen as a climate solution that should be credited to the livestock sector. Livestock advocates also tend to emphasise the social and nutritional benefits of animal-sourced foods – benefits that in their view may outweigh the climate benefits of cutting livestock production more rapidly.

An opposing interpretation instead emphasises the risk of near-term catastrophic climate tipping points. This argument says that since the rate of change of methane emissions strongly and rapidly influences warming, urgent and significant reductions in anthropogenic methane emissions (from ruminant production as well as other methane sources such as rice fields and fossil fuels) should be used as an emergency lever to minimise climate warming in the short term (i.e. the next couple of decades), buying more time to bring down CO_2 emissions as well in the long term[12]. This interpretation lends itself to arguments in favour of rapid and significant reductions in ruminant production. Critics of the livestock industry sometimes argue that the sector is using GWP* as an excuse to avoid cutting livestock methane emissions more quickly[13], and note that GWP* shows that any expansion in methane emissions – for example, if production of beef were to increase[14] – would have a significant and rapid warming effect.

The conclusions that stakeholders reach about how much and how quickly ruminant production should be curtailed on the grounds of methane emissions are also influenced by other beliefs about livestock, such as whether red meat is seen as unhealthy or as an important source of nutrients (discussed in more detail below), and whether grazing is seen as beneficial or detrimental to soil health and biodiversity.

Another area of controversy in calculating the climate impacts of food relates to where the system boundaries should be drawn. According to the carbon opportunity cost concept, a food's carbon footprint should account not only for direct production emissions, but also for the carbon that could be sequestered if native ecosystems (e.g. wild grasslands or forests) were permitted to occupy the land again. Note that while regrowth of biomass could continue for decades, it would ultimately reach a saturation point. Carbon opportunity cost calculations show that beef tends to have a particularly high carbon cost, partly because of beef cattle's large land requirements per gram of protein compared to other food categories (as shown in Figure 3)[15]. However, the carbon opportunity costs are much higher for those beef production systems that are very extensive (e.g. in Brazil) and where there would hence be more land for native vegetation to regrow, compared to others (e.g. in the Netherlands)[16]. Whether this calculation leads to the conclusion that ruminant production should be reduced (and to what extent, and in which regions) depends on other assumptions about the value of wild landscapes (including both grasslands and forests) and the species that live in them, the importance of ruminant meat for human nutrition, and the urgency of reducing methane emissions at the global level from both livestock and other sectors such as fossil fuels.

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12 Here are some examples of the argument that methane reductions are an important short-term lever for climate mitigation. Changing Markets Foundation (2021), Blindspot: How lack of action on livestock methane undermines climate targets (TABLE summary), says "A rapid reduction in methane emissions may provide opportunities to slow the rate of warming, allowing a window for more fundamental changes in society to take place." Brunner, C. (2022), Climate action: Methane is our most powerful lever, says "reducing methane emissions is a powerful way to rapidly and effectively prevent global warming… It has long been obvious what needs to be done: significantly reduce our consumption of meat and dairy products and avoid wasting food." UNEP (2021), Global Methane Assessment, argues that reducing global methane emissions by 45% this decade is possible and could avoid nearly 0.3°C of global warming by 2045; it recommends both supply-side measures, such as changes to livestock management, and demand-side measures, including reducing food waste and eating less meat and dairy.

13 See Boren, Z. (2022), How the beef industry is trying to change the maths of climate change, published by Greenpeace.

14 For discussion of livestock industry expansion targets, see Sharma, S. (2021), Emissions Impossible Europe (TABLE summary) and Christen, C. (2021), Investigation: How the Meat Industry is Climate-Washing its Polluting Business Model (TABLE summary).

15 Poore, J. and Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360(6392), pp.987-992.

16 Ritchie, H. (2021), What are the carbon opportunity costs of our food? Our World in Data.

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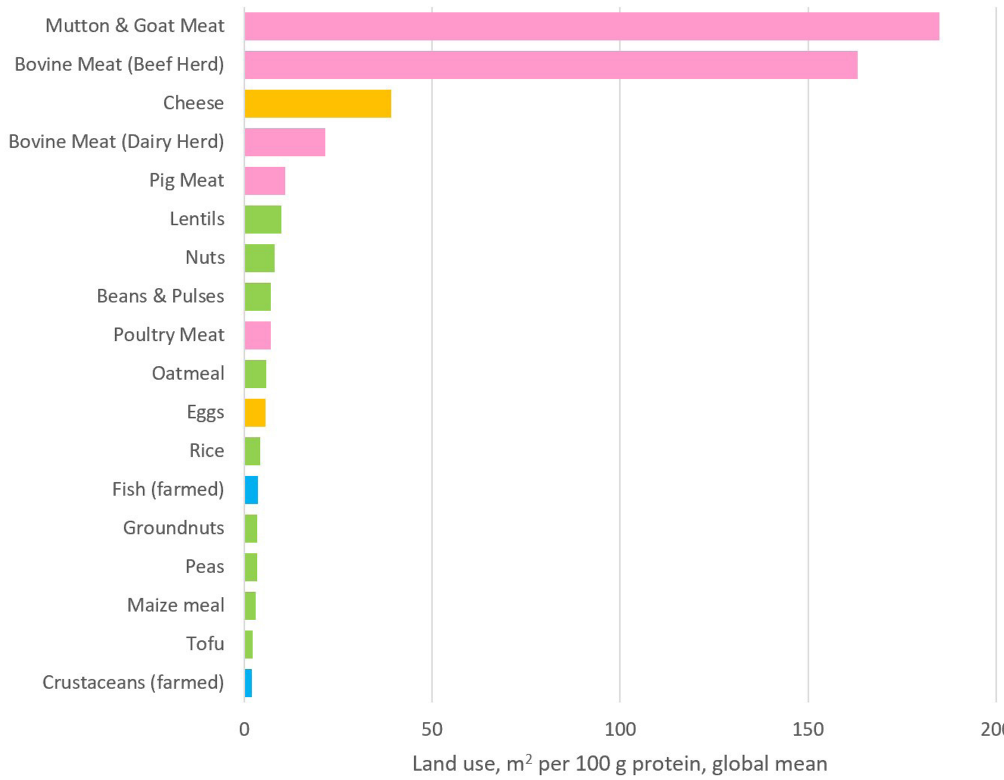

Figure 3: Global mean land use of various protein sources across a range of countries and management practices, m² per 100g of protein. The graph does not distinguish between arable and grazed land. Pink bars indicate meat; blue, seafood; orange, other animal products; green, crops. Data source: Poore and Nemecek (2018) with additional data provided directly by Joseph Poore and protein content data from the FAO's Food Composition Tables. Figure produced by TABLE.

Another viewpoint is that the scope of emissions calculations should include the increase in soil carbon that ruminants, under some grazing strategies, can induce (e.g. under "**regenerative**" management). The potential of grazing ruminants to sequester carbon in some contexts is often emphasised by those who also believe grazing brings benefits for soil health, on-farm biodiversity and ecosystems function (for example with ruminants mimicking the ecological function of wild herbivores), culture, the rural economy and the aesthetic value of landscapes – with many advocates for grazing livestock also arguing that these broader benefits are at least as important as, or perhaps more important than, the carbon footprint. Some studies report that the carbon sequestration effect can either partially or completely offset the methane and other emissions from ruminants[17,18] and some regenerative livestock farmers believe that their practices can create an indefinite build-up of soil carbon stocks[19]. However, there is uncertainty around the extent to which ruminants can induce permanent and reliable carbon sequestration. The 2017 FCRN report ***Grazed and Confused*** concluded that soil carbon sequestration on grazed land happens only in specific conditions and is likely time-limited, since soils tends to reach an equilibrium in their carbon content after some years or decades. More recently, a 2022 review[20] found that livestock grazing can lead to either loss or sequestration of soil carbon, depending on many variables such as climate, vegetation and grazing duration

17 Stanley, P.L., Rowntree, J.E., Beede, D.K., DeLonge, M.S. and Hamm, M.W. (2018), Impacts of soil carbon sequestration on life cycle greenhouse gas emissions in Midwestern USA beef finishing systems. *Agricultural Systems*, 162, pp.249-258 (TABLE summary).

18 Rowntree, J.E., Stanley, P.L., Maciel, I.C., Thorbecke, M., Rosenzweig, S.T., Hancock, D.W., Guzman, A. and Raven, M.R. (2020), Ecosystem impacts and productive capacity of a multi-species pastured livestock system. *Frontiers in Sustainable Food Systems*, 4, p.232 (TABLE summary).

19 For just one example, see the October 2022 FAI Farms webinar Regen Dairy round-the-world tour.

20 Bai, Y. and Cotrufo, M.F. (2022), Grassland soil carbon sequestration: Current understanding, challenges, and solutions. Science, 377(6606), pp.603-608.

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and intensity (heavy and moderate grazing intensity tends to be associated with reductions in soil carbon stocks compared to lighter grazing intensity). It also notes that soil carbon storage in grasslands could be substantially increased by adopting improved grazing management practices, such as rotational grazing. It estimates that grassland restoration (involving practices such as sowing legumes or grasses and optimising grazing intensity) could "realistically"[21] sequester 6.8 billion t CO_2 equivalents per year – i.e. around 14% of 2019 global greenhouse gas emissions[22]. It is unclear how long this rate of sequestration could continue; accounting for the potential saturation of soil carbon significantly reduces the estimated global contribution that soils could make to climate mitigation[23].

Livestock's sustainability performance also depends on the source of animal feed. The concept of **feed-food competition** refers to the feeding of human-edible crops to livestock. Since livestock use energy in digestion, movement, the production and maintenance of non-edible body parts and so on, they provide less energy and total protein for humans than would be available if people ate the crops directly. The production of some feed crops, such as soy, is linked to deforestation in some countries. Estimates of the proportion of edible crops eaten directly by people as food vary, but one study[24] calculates that people consume 55% of crop calories, 40% of crop protein and 67% of crop weight directly[25]. If all crops were eaten by people, overall protein availability would double and calorie supply would rise 70% (a conclusion slightly nuanced by the discussion of protein quality above)[26]. According to the **Feed Conversion Ratio** (FCR) (a measure with some limitations), beef cattle typically require 6.0–10.0 kg of feed to put on 1 kg of body weight, with the range being approximately 2.7–5.0 for pigs and 1.7–2.0 for chickens[27]. These figures are often interpreted to mean that ruminants are the least efficient kind of livestock and chicken the most efficient. Another factor is that animals raised in intensive systems tend to expend less energy and hence consume less feed than free-range animals, albeit with likely trade-offs for their welfare.

An alternative interpretation is that ruminants are *more* efficient than monogastrics, because ruminants increase the global availability of human-edible protein by generating 1 kg of protein (meat and dairy) per 0.6 kg of protein in human-edible feed, which is possible because they also consume grass and other inedible feedstuffs[28]. By this measure, monogastrics appear less efficient, requiring 2 kg of protein in human-edible feed to produce 1 kg of protein (meat and eggs). This argument can be followed to the conclusion that "livestock on leftovers" offers the most sustainable role for animals in the food system. Here, livestock would only eat inedible feedstuffs, such as grass, food waste, agricultural residues or industrial by-products. Indeed, a clearer name for the scenario might be "livestock on

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21 The relevant quote from the paper is: "Potential soil carbon sequestration capacities can be categorized as theoretical, realistic, or achievable. Theoretical soil carbon sequestration capacity refers to the estimate of restoring all soils to their natural capacity or even enhancing it through management interventions, realistic soil carbon sequestration capacity refers to the optimistic value accounting for social and economic constraints, and achievable capacity is the value of a pragmatic scenario based on the current trends. At the global scale, the mean theoretical, realistic, and achievable capacities of SOC sequestration with grassland restoration are estimated to be 10.2, 6.8, and 3.4 billion t CO_2 equivalents per year (CO_2e year^{-1}), respectively."

22 2019 global greenhouse gas emissions = 49.76 billion tonnes CO_2 eq. measured using GWP_{100}. Figure taken from Greenhouse gas emissions - Our World in Data.

23 Moinet, G.Y., Hijbeek, R., van Vuuren, D.P. and Giller, K.E. (2023), Carbon for soils, not soils for carbon. *Global Change Biology*, Early View.

24 Cassidy, E.S., West, P.C., Gerber, J.S. and Foley, J.A. (2013), Redefining agricultural yields: from tonnes to people nourished per hectare. *Environmental Research Letters*, 8(3), p.034015 (TABLE summary).

25 The study did not include forage crops or crop residues in its tally of edible crops.

26 Cassidy, E.S., West, P.C., Gerber, J.S. and Foley, J.A. (2013), Redefining agricultural yields: from tonnes to people nourished per hectare. *Environmental Research Letters*, 8(3), p.034015 (TABLE summary).

27 Fry, J.P., Mailloux, N.A., Love, D.C., Milli, M.C. and Cao, L. (2018), Feed conversion efficiency in aquaculture: do we measure it correctly? *Environmental Research Letters*, 13(2), p.024017 (TABLE summary).

28 Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C. and Gerber, P. (2017), Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security*, 14, pp.1-8 (TABLE summary). Note that the paper defines soybean cakes as inedible. If soybean cakes were classed as edible, then ruminants globally require 1.0 kg of protein from edible feed to produce 1.0 kg of protein from meat and dairy.

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grass and leftovers"[29]; it is also known as the "ecological leftovers" approach[30].

A livestock on leftovers approach could use less arable land per person (but more land overall) than a purely vegan diet (which itself would use less arable land than today's diet – discussed further below). Adoption of this approach could also reduce several other environmental impacts relative to today's production methods. Using the livestock on leftovers approach at the global level would require animal protein consumption to fall relative to today's levels. One study suggests livestock on leftovers could provide between 9 and 23 g of protein[31] from animal sources, relative to current global average supplies of 27 g of animal protein (excluding fish) and daily protein requirements (from any source) of 50-60 g per person per day[32]. Therefore, meat consumption would have to drop in the highest consuming countries – for example, current supplies of animal protein (as opposed to total protein)[33] are 63 g per person per day in North America.

One argument against the livestock on leftovers approach is that not all types of livestock feed, e.g. grains, soymeal and fishmeal, are of a grade or quality suitable for direct human consumption and therefore it makes sense to feed them to animals. However, there is not a clear distinction between edible and non-edible crops: the categorisation may depend on local regulations (e.g. due to labelling policies for genetically modified varieties[34]), cultural trends[35] and processing techniques[36]. Furthermore, in a livestock on leftovers scenario, existing arable land may be repurposed to grow different crops more suitable for meeting human food needs.

In summary, views of livestock fed on human-edible crops vary. To some who believe that the projected increase in demand for meat is unlikely to change, crop-fed livestock offer a more efficient production method than grass-fed livestock in terms of emissions and land use per kg of product and would protect nature by preventing some expansion of grazing land. The crop-fed livestock production system is sometimes seen as a "buffer", adding resilience to the food system by releasing crops for direct human consumption when supplies are low[37]. To others, particularly those who believe demand for meat can be moderated, feeding crops to livestock is a waste of edible food that people could consume directly.

The question of how much meat we should eat – and of what type – is also strongly linked to how much land is available. According to at least one study, global adoption of the meat-heavy diets of countries such as New Zealand, Argentina and Australia would require more land area than the planet actually has[38]. Hence, there are physical limits to the worldwide adoption of the meat-heavy diets that are currently widespread in many high-income countries

29 With thanks to Richard Young of the Sustainable Food Trust for this suggestion.

30 Garnett, T. (2009), Livestock-related greenhouse gas emissions: impacts and options for policy makers. *Environmental science & policy*, 12(4), pp.491-503.

31 Protein content, not total food weight.

32 Van Zanten, H.H., Herrero, M., Van Hal, O., Röös, E., Muller, A., Garnett, T., Gerber, P.J., Schader, C. and De Boer, I.J. (2018), Defining a land boundary for sustainable livestock consumption. Global Change Biology, 24(9), pp.4185-4194.

33 Excluding fish.

34 See the TABLE blog Fraanje, W. (2020), Soy in the UK: What are its uses?

35 See the TABLE blog O'Sullivan, C. (2019), Can we have our farmed salmon and eat it too? for a discussion of how marketing can influence demand for so-called "unmarketable fish" species.

36 See pages 61-63 of Garnett, T. (2007), Meat and dairy production & consumption: Exploring the livestock sector's contribution to the UK's greenhouse gas emissions and assessing what less greenhouse gas intensive systems of production and consumption might look like, Food Climate Research Network.

37 The mechanism could be changes in food prices or government policy. See for example Speedy, A.W. (2003), Global production and consumption of animal source foods. *The Journal of nutrition*, 133(11), pp.4048S-4053S. A historical example of this strategy is Denmark's WWI policy of switching to low-meat diets, which averted starvation while animal feed supplies were limited due to a blockade on imports. See Hindhede, M. (1920), The effect of food restriction during war on mortality in Copenhagen (PDF version here).

38 Alexander, P., Brown, C., Arneth, A., Finnigan, J. and Rounsevell, M.D. (2016), Human appropriation of land for food: The role of diet. *Global Environmental Change*, 41, pp.88-98.

(and towards which many other regions are moving[39]), at least with current production systems. Rising demand for livestock is projected to conflict with ecosystems conservation goals – especially since many scientists argue that large areas of biodiverse ecosystems must be conserved[40]. There is broad consensus among many researchers and international bodies, including the **IPCC**, **IPBES** and the **FAO**, that diets containing lower levels of animal products than current "Western" diets can be healthy and offer environmental benefits.

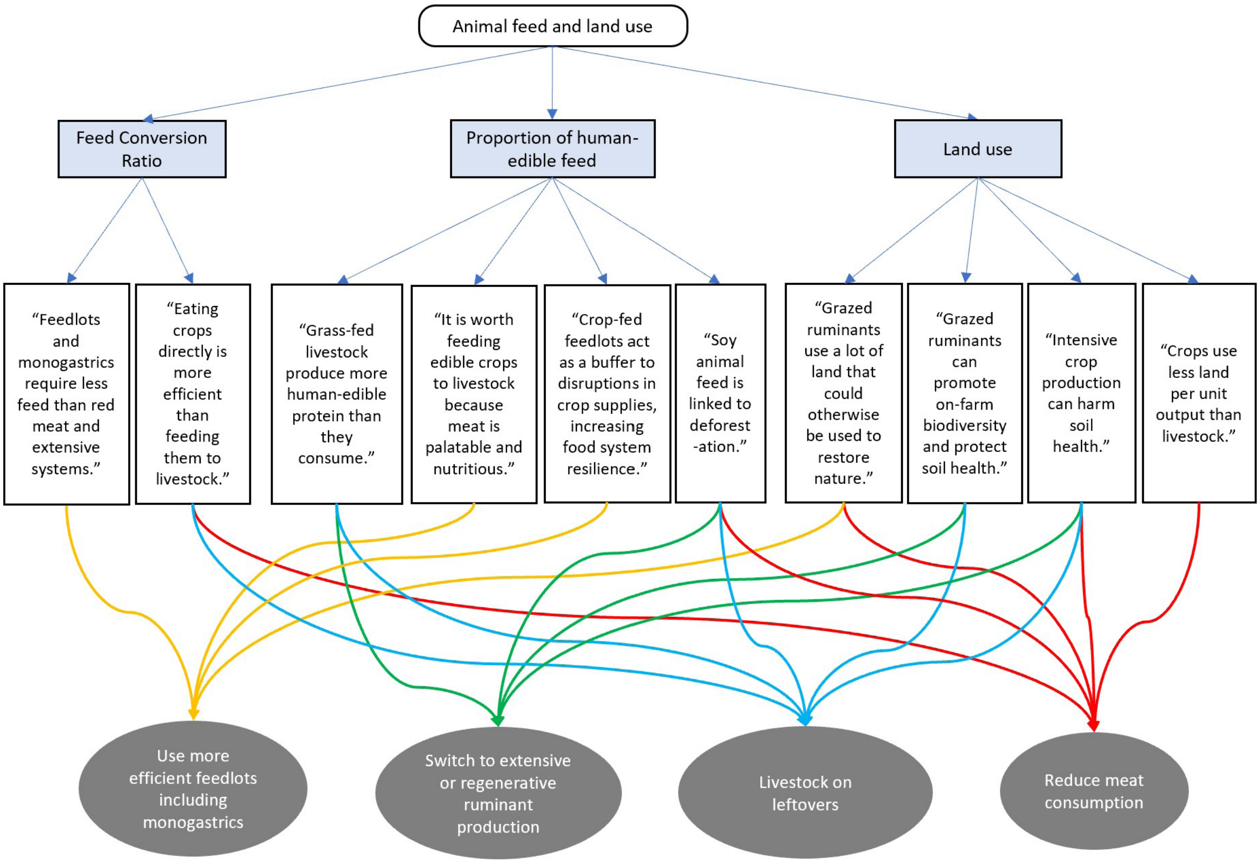

Figure 4: Some interpretations of issues around animal feed and the land use of livestock. Graphic produced by TABLE.

Meat's connection to human health

The impact that meat consumption has on human health depends not just on the type and quantity of meat consumed, but also on what other foods people eat – factors that all depend heavily on social and economic context.

In lower income countries, for instance, diets tend to obtain a greater share of calories from foods high in carbohydrates, such as cereals, roots and tubers, and a lower share from meat, seafood, eggs and dairy products, in comparison to richer countries[41]. Furthermore, total dietary supplies of calories, protein and fat (from any source) are

39 Parlasca, M.C. and Qaim, M. (2022), Meat consumption and sustainability. *Annual Review of Resource Economics*, 14, pp.17-41 (TABLE summary).

40 Allan, J.R., Possingham, H.P., Atkinson, S.C., Waldron, A., Di Marco, M., Adams, V.M., Butchart, S.H., Kissling, W.D., Worsdell, T., Gibbon, G., Kumar, K., Mehta, P., Maron, M., Williams, B. A., Jones, K. R., Wintle, B. A., Reside, A. E. and Watson, J. E. M. (2022), The minimum land area requiring conservation attention to safeguard biodiversity. *Science,* 376(6597), pp.1094-1101 (TABLE summary).

41 Ritchie, H., Rosado, P. and Roser, M., Diet Compositions, Our World in Data.

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lower in lower income countries[42]. Dietary health concerns in this context are primarily about **malnutrition**, which encompasses inadequate intake of calories or macronutrients such as protein, essential amino acids or fibre as well as insufficient intake of a variety of micronutrients such as iron. In this context, meat and other animal sourced foods can be important sources of both macro- and micronutrients.

As countries grow richer, diets tend to become more diverse in nutrient-rich foods, including both animal sourced foods and, for instance, fruit[43]. On one hand, this greater overall diversity of food (including but not limited to meat) can contribute to adequate intakes of calories and protein as well as to the supply of micronutrients that are important for health, thus reducing the incidence of diseases linked to undernutrition. On the other, once animal sourced food intakes rise beyond a certain level, they become more likely to contribute to "diseases of excess" such as colorectal cancer, which has been linked to processed meat consumption[44]. However, as with lower income contexts, the health impacts of meat and other animal sourced foods still depend on the forms in which they are consumed (processing, preparation method and so forth) as well as the overall composition of the diet (in terms of both energy intake and nutrients) and an individual's overall lifestyle. In other words, it is hard to separate out the health effects of animal source foods from the many other 'confounding factors' (such as smoking, socioeconomic status and body weight) which may contribute to or reduce health risks.

Although diets in richer countries are more diverse and more likely to provide adequate energy and protein, a recent study shows that micronutrient deficiencies are widespread even in rich countries (but even more so in lower income countries)[45]. Some argue that it is important in both low and high income contexts to ensure adequate intake of nutrient-dense foods[46]. This includes both animal foods, e.g. organ meat, for their provision of nutrients such as vitamin A and iron in forms that are more readily absorbable than plant-based sources, as well as plant-based foods such as dark green leafy vegetables for their calcium and folate content.

There are also debates about how farming methods influence nutrition, although it is difficult to tease out the effects of farming systems on the nutritional profile of foods and, furthermore, to link those effects to health outcomes. For instance, it is commonly argued by pro-grazing advocates in high-income countries that grass-fed meat is healthier than grain-fed, for example on the grounds that higher omega-3 to omega-6 ratios are found in grass-fed meat (shown by several studies, although these studies do not link the nutritional profiles to health outcomes[47,48]). Note, however, that the amount of omega-3 fatty acids in beef is significantly lower than in other sources such as fish (discussed further below)[49].

Another link between meat production methods and human health is the risk of **zoonotic diseases**, i.e. infectious diseases that spread between animals and people. The evidence remains unclear as to whether intensive or

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42 Roser, M., Ritchie, H. and Rosado, P., Food Supply, Our World in Data.

43 See Breewood, H. (2018), What is the nutrition transition? TABLE, University of Oxford.

44 Bradbury, K.E., Murphy, N. and Key, T.J. (2019), Diet and colorectal cancer in UK Biobank: a prospective study. *International journal of epidemiology*, dyz064 (TABLE summary).

45 Stevens, G.A., Beal, T., Mbuya, M.N., Luo, H., Neufeld, L.M., Addo, O.Y., Adu-Afarwuah, S., Alayón, S., Bhutta, Z., Brown, K.H. and Jefferds, M.E. (2022), Micronutrient deficiencies among preschool-aged children and women of reproductive age worldwide: a pooled analysis of individual-level data from population-representative surveys. *The Lancet Global Health*, 10(11), pp.e1590-e1599 (TABLE summary).

46 Beal, T. and Ortenzi, F. (2022), Priority micronutrient density in foods. *Frontiers in nutrition*, p.379. See also the TABLE Letterbox Vegan or flexitarian - which diet is healthier?, to which Flaminia Ortenzi has contributed.

47 Lukic, M., Trbovic, D., Karan, D., Petrovic, Z., Jovanovic, J., Milijasevic, J.B. and Nikolic, A. (2021), The nutritional and health value of beef lipids-fatty acid composition in grass-fed and grain-fed beef. *IOP Conference Series: Earth and Environmental Science,* 854(1), p. 012054.

48 Van Vliet, S., Provenza, F.D. and Kronberg, S.L. (2021), Health-promoting phytonutrients are higher in grass-fed meat and milk. *Frontiers in Sustainable Food Systems*, p.299.

49 National Institutes of Health, Omega-3 Fatty Acids: Fact Sheet for Health Professionals.

extensive livestock systems present the greater risk. A recent review[50] suggests that extensive systems where livestock have more contact with wild animals are more likely to pick up diseases in the first place, but that intensive enclosed systems are more likely to spread diseases that do arise, due to greater genetic uniformity of livestock, higher stocking densities and often lower welfare conditions. The review makes the point that systems that combine features of both types of farming might have even higher risks.

Social and ethical issues around meat

There are strong differences in opinion as to whether it is ethical to kill animals for food and, if so, how best to rear livestock. Social attitudes differ: some people abstain from animal products altogether. Others may avoid eating products from the animals they see as most sentient (e.g. pigs), and instead choose to eat animals that they see as having lower moral standing (e.g. mussels). Another approach is to advocate for better welfare conditions on farms – however, understandings of **animal welfare** vary, with some placing more emphasis on freedom from discomfort or stress (which may lead to the conclusion that enclosed, temperature-controlled farms are best), and others advocating for conditions that permit "natural" behaviours (a requirement that may favour free range production). Others believe it is better to minimise the number of lives that are taken for human food – the conclusion here is sometimes that the largest animals which can feed the most people per life, such as cattle, are the most ethical source – although this argument is rarely extended to species that are endangered, difficult-to-domesticate or perceived as charismatic, such as **whales**. Insect and small mammal deaths and injuries, such as those that occur during crop maintenance and harvest, are often used to argue against vegan diets. However, it is not common for these deaths to be seen as morally equivalent to livestock deaths; furthermore, meat from livestock raised primarily on grain or soy will require more crops, and hence likely result in more insect and animal deaths, than a plant-based option. Even **rewilding** raises animal welfare concerns, since wild animals also experience fear, pain, illness, hunger and violent deaths (possibly to a greater extent than farmed animals), and since rewilding projects sometimes involve culling (e.g. of invasive species).

People working in meat supply chains face struggles of their own. Slaughterhouse workers face high rates of injury[51], psychological harm[52] and a high risk of the transmission of infectious diseases such as COVID due to crowded working conditions[53]. Meanwhile, although farmers often enjoy strong public support[54,55], some types of livestock farmers often struggle to make a living (indeed, in the UK, subsidies currently account for 90% of sheep farm income[56]) or are locked into debt or contracts with large corporations[57].

Corporate control of food supply chains is another factor driving debates around livestock and also around plant-based and cell-based alternatives (see below). Concerns include: that aggressive marketing drives meat consumption

50 Bartlett, H., Holmes, M.A., Petrovan, S.O., Williams, D.R., Wood, J.L. and Balmford, A. (2022), Understanding the relative risks of zoonosis emergence under contrasting approaches to meeting livestock product demand. *Royal Society Open Science*, 9(6), p.211573 (TABLE summary).

51 Milmo, C., Heal, A. and Wasley, A. (2018), Revealed: Heavy toll of injury suffered by slaughter workers in Britain's £8bn meat industry, newspaper.

52 Heanue, O. (2022), For Slaughterhouse Workers, Physical Injuries Are Only the Beginning. OnLabor.

53 van der Zee, B., Levitt, T. and McSweeney, E. (2020), 'Chaotic and crazy': meat plants around the world struggle with virus outbreaks. The Guardian.

54 Irons, A. (2021), Public opinion of British farmers is world-leading, survey shows. Cornwall Live.

55 Moore, T. (2020), Public Attitudes about Farmers and Farming: A Golden Opportunity. Farm Bureau.

56 O'Neill, C., Lim, F.K., Edwards, D.P. and Osborne, C.P., 2020. Forest regeneration on European sheep pasture is an economically viable climate change mitigation strategy. *Environmental Research Letters*, 15(10), p.104090 (TABLE summary).

57 Newton, P. and Blaustein-Rejto, D. (2021), Social and economic opportunities and challenges of plant-based and cultured meat for rural producers in the US. *Frontiers in Sustainable Food Systems*, 5, p.10 (TABLE summary).

higher than it otherwise would be[58]; that supply chain consolidation gives a small number of people disproportionate power[59]; and that large corporations are (mis)appropriating terms such as "regenerative" or "agroecological" to deflect from the need for dietary change or to increase sales of products now marketed as sustainable[60,61,62].

Livestock also play an important role in many cultures and societies – both for the food they produce, and for the traditions and livelihoods connected to some systems of farming livestock, for example pastoralism.

Fish

Many of the debates around livestock are mirrored in the fish and seafood sector. In this case, the two main production options are harvesting wild seafood or using **aquaculture**.

Fish and the environment

Wild and farmed fish both have environmental impacts.

34% of wild fish stocks are overfished[63], species such as turtles and seabirds are accidentally caught as bycatch[64], and industrial fishing fleets (including those supplying fishmeal) have been accused of harming the livelihoods of people who rely on small fisheries for food or income[65].

Aquaculture often uses wild fish (much of it suitable for direct human consumption) as a feedstock and hence can increase pressure on wild stocks relative to wild catch, although land-based crops are also used as feeds[66]. Not all aquaculture systems have the same impacts: enclosed ("recirculating") aquaculture systems are less vulnerable than open-water aquaculture systems to the effects of climate change, parasites and so on, but they also need more energy to continuously circulate and filter the water.

A 2021 global review[67] found that the seafoods with the lowest impacts tend to be farmed bivalves (e.g. mussels) and farmed seaweeds, with both having lower average greenhouse gas emissions, water use and land use than other forms of seafood. Farmed bivalves and seaweeds, along with some other types of farmed fish that do not require feeding, extract more nitrogen and phosphorus from the environment than they emit. Unfed bivalve aquaculture can hence protect waters against eutrophication caused by nitrogen runoff from the land[68]. Unfed aquaculture may also

58 Howard, P. (2022), The politics of protein: examining claims about livestock, fish, 'alternative proteins' and sustainability. IPES-Food (TABLE summary).

59 TABLE Feed podcast, Phil Howard on Corporate Consolidation.

60 Wozniacka, G. (2019), Big Food is Betting on Regenerative Agriculture to Thwart Climate Change. Civil Eats (TABLE summary).

61 Walmart (2020), Walmart Sets Goal to Become a Regenerative Company. (TABLE summary.)

62 Fisher, T. (2022), Decoupling Desire: How can the advertising sector promote better, or less, consumption? TABLE blog.

63 Ritchie, H. and Roser, M. (2021), Fish and Overfishing, Our World in Data.

64 Burgess, M.G., McDermott, G.R., Owashi, B., Reeves, L.E.P., Clavelle, T., Ovando, D., Wallace, B.P., Lewison, R.L., Gaines, S.D. and Costello, C. (2018), Protecting marine mammals, turtles, and birds by rebuilding global fisheries. *Science*, 359(6381), pp.1255-1258 (TABLE summary).

65 Greenpeace International (2019), Fishmeal industry stealing regional food and livelihoods in West Africa.

66 TABLE blog O'Sullivan, C. (2019), Can we have our farmed salmon and eat it too?

67 Gephart, J.A., Henriksson, P.J., Parker, R.W., Shepon, A., Gorospe, K.D., Bergman, K., Eshel, G., Golden, C.D., Halpern, B.S., Hornborg, S. and Jonell, M. (2021), Environmental performance of blue foods. *Nature,* 597(7876), pp.360-365.

68 Willer, D.F. and Aldridge, D.C. (2020), Sustainable bivalve farming can deliver food security in the tropics. *Nature Food*, 1(7), pp.384-388 (TABLE summary).

reduce pressure on agricultural land, if it replaces some meat or crop consumption[69].

Health issues with seafood

Consumption of fish is associated with several beneficial health outcomes including lower risk of death and lower risk of coronary heart disease, colorectal cancer and stroke[70]. These positive health outcomes might be due to the high levels of the omega-3 fatty acids EPA and DHA[71] found in some seafoods such as oily fish (e.g. anchovies, herring, salmon) and some bivalves (e.g. oysters)[72]. This EPA and DHA is generally originally produced by algae that is eaten by fish. The ratio of omega-3 to omega-6 in fish depends on the feed source – for instance, farmed salmon has been found to have a significantly lower proportion of omega-3 than wild salmon[73]. Contamination with mercury and other pollutants is a risk with seafood, particularly for fish high on the food chain such as shark or tuna, so limiting intake of these foods is sometimes recommended, especially during pregnancy[74]; some manufacturers of EPA and DHA supplements made from algae base their marketing[75] on claims that these supplements, being low in mercury and other heavy metals, are therefore safer sources of EPA and DHA than seafood. Shellfish have also been linked to food poisoning through "red tide" algal blooms[76]. Furthermore, shellfish allergies are common.

Balancing seafood sustainability concerns

The way in which people balance different concerns about seafood relating to its environmental, health and animal welfare impacts will depend on their personal priorities and values. For example, one strategy is to eat seafood lower on the food chain, such as mussels or anchovies, for environmental reasons (being quicker to reproduce, these species may be more resilient to fishing pressure[77]), for health reasons (lower mercury content with high omega-3 content) or for ethical reasons (it is often argued that mussels are not sentient enough to experience suffering, since they lack a central nervous system[78]). Another approach, sometimes recommended by industry bodies, is to assume that there is no single most sustainable type of seafood – rather, since fishing methods and stock levels are constantly changing, the optimum choice will also change over time. The Marine Stewardship Council says[79] "there is no such thing as a sustainable species, only sustainable stocks"; meanwhile, the Marine Conservation Society publishes a regularly updated seafood sustainability ranking[80].

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69 Froehlich, H.E., Runge, C.A., Gentry, R.R., Gaines, S.D. and Halpern, B.S. (2018), Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proceedings of the National Academy of Sciences,* 115(20), pp.5295-5300 (TABLE summary).

70 Clark, M.A., Springmann, M., Hill, J. and Tilman, D. (2019), Multiple health and environmental impacts of foods. *Proceedings of the National Academy of Sciences*, 116(46), pp.23357-23362 (TABLE summary). The paper assesses the health outcomes of the consumption of one additional serving of a food, relative to average observed intakes in Westernised diets.

71 EPA = eicosapentaenoic acid and DHA = docosahexaenoic acid.

72 Siegfried, A. (2022), A Nutritionist's Guide to Omega-3's and Sustainable Seafood, Marine Stewardship Council.

73 Jensen, I.J., Eilertsen, K.E., Otnæs, C.H.A., Mæhre, H.K. and Elvevoll, E.O. (2020), An update on the content of fatty acids, dioxins, PCBs and heavy metals in farmed, escaped and wild Atlantic salmon (Salmo salar L.) in Norway. *Foods*, 9(12), p.1901.

74 National Health Service (2022), Fish and shellfish.

75 See for example the paid advertorial Venus, L. (2021), The Lies We're Told About Fish Oil: Mercury, Pollution, And Fish Farms, Plant Based News.

76 Centers for Disease Control and Prevention (2022), Food Poisoning from Seafood.

77 Beaty, J. (2014), Sustainable Seafood, Sailors for the Sea.

78 I Am Going Vegan blog, What Exactly Is an Ostrovegan or Bivalvegan?

79 Marine Stewardship Council, Are Oysters Sustainable?

80 Marine Conservation Society, Good Fish Guide.

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Plants

The sustainability issues associated with livestock have led to vegetarian, vegan and low-meat diets and foodstuffs receiving much attention as potentially more sustainable options than the animal product-rich dietary patterns that prevail in high income countries and among the affluent across the world. Meanwhile, meat and dairy consumption remains lower – but is rising – in many low- and middle-income countries. This section focuses mostly on plant-based diets and foodstuffs chosen for their health or environmental attributes – and usually framed as an "alternative" to Westernised diets and styles of eating – as opposed to diets which are largely plant-based because of poverty, a lack of access to animal-sourced foods, or adherence to religious dietary requirements.

Plant-based alternatives to animal-sourced foods include several categories: relatively unprocessed options such as pulses and nuts; traditional plant-based foods which have long been used (particularly in Asian cuisines) either to imitate animal-sourced foods, such as mock duck made from seitan, or as foods in their own right, such as tofu, nattō, falafel and tempeh; and new forms of (often) highly processed plant-based analogues intended to imitate the taste and texture of meat or other animal-sourced foods. Different sustainability and health concerns apply to each of these categories. Furthermore, the issues that arise regarding plant-based *foods* and plant-based *diets* differ to some extent, although there is considerable overlap. Some of the debates are illustrated in Figure 5.

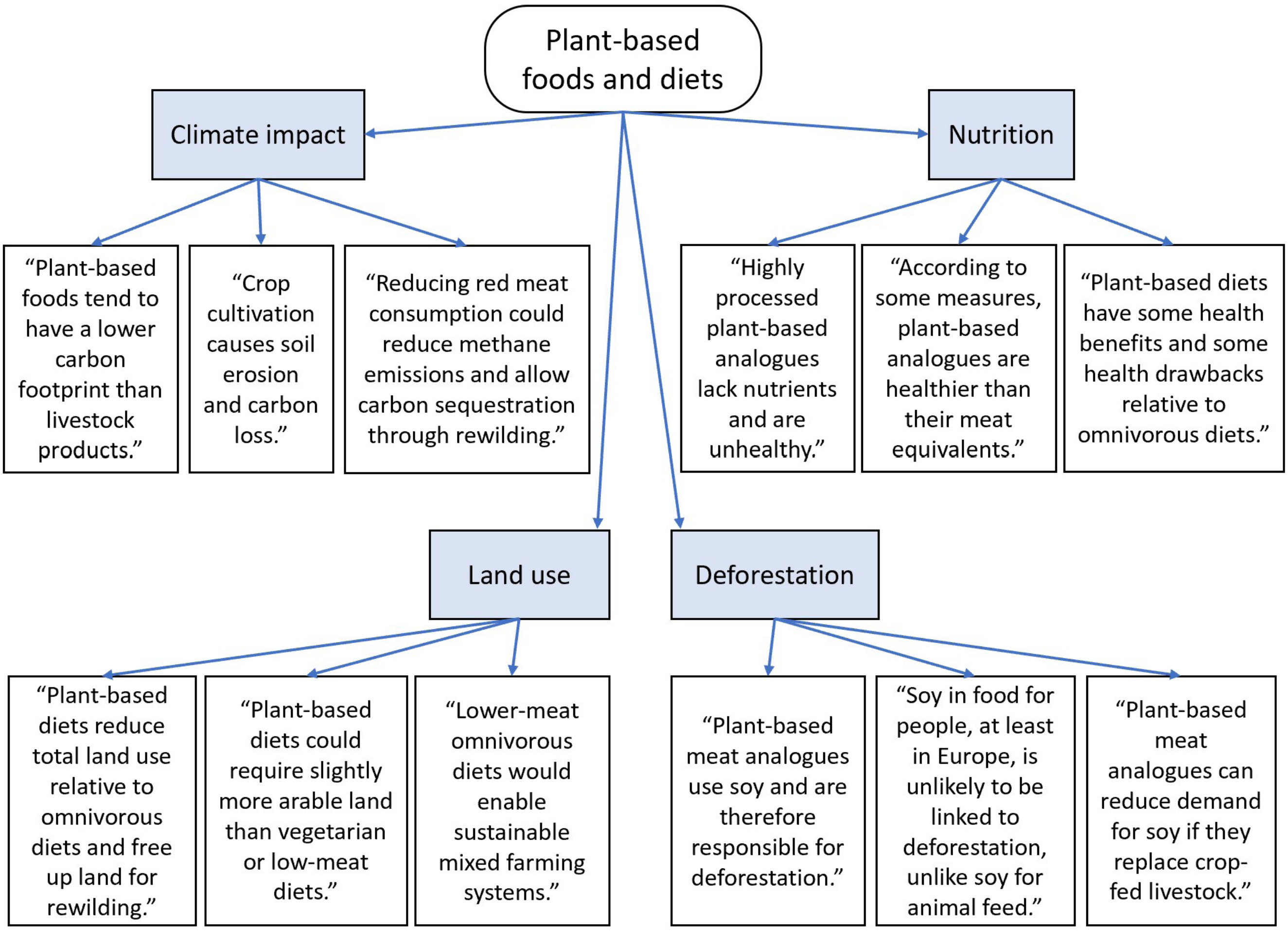

Figure 5: Differing interpretations of sustainability concerns relating to plant-based foods and diets. Each statement represents a different subjective viewpoint. Graphic produced by TABLE.

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The very notion of a plant-based food as an "alternative" to an animal-source food implicitly frames animal-sourced foods, and the format in which they are often consumed (e.g., with meat as the centrepiece of a meal), as the norm. The term "alternative" is itself somewhat tricky to define, as it encompasses foods which might share many or only one characteristic with their animal-soured equivalents, for example function, taste, texture or nutritional profile.

Environmental implications of plant-based foods

The motivation for shifting diets towards plants – aside from animal welfare concerns, described above – is generally that it is seen as more efficient to eat crops than to feed those crops to livestock. Compared on the basis of their protein content, most plant sources of protein tend to have substantially lower carbon emissions, land use, acidification potential and eutrophication potential than animal sources[81]. There are some exceptions to this general rule: nuts and poultry, for instance, have similar land use requirements; and nuts generally use more freshwater (relative to local availability) than most other protein sources[82]. While individual plant-based foods have been linked to certain harms (such as illegal deforestation taking place to grow avocados)[83], on the whole, real or modelled diets lower in animal products tend to have lower carbon footprints[84] and other environmental impacts than omnivorous diets[85,86,87].

Modelling studies show that diets lower in animal products could use much less global agricultural land than today, mainly through a substantial reduction in pasture area but also because less arable land is required to grow livestock feed[88,89,90,91]. For example, one study finds that excluding animal products from diets would decrease total global agricultural land use by 76% and arable land use by 19%, relative to today[92]. Another study[93] finds that the minimum per capita cultivated *cropland* use is offered not by vegan diets, but by those that are vegetarian or that contain small amounts of meat. This is because vegetarian and omnivorous diets can use food from small areas of perennial cropland (e.g. hay to feed dairy cows) or from pasture. However, *total* per capita land use is still lowest for vegan diets in this study.

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81 Poore, J. and Nemecek, T. (2018), Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392), pp.987-992.

82 Ritchie, H. and Roser, M. (2022), Environmental Impacts of Food Production, Our World in Data.

83 See the TABLE blog Breewood, H. (2018), Are modern plant-based diets and foods actually sustainable?

84 Scarborough, P., Appleby, P.N., Mizdrak, A., Briggs, A.D., Travis, R.C., Bradbury, K.E. and Key, T.J. (2014), Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. *Climatic change*, 125(2), pp.179-192 (TABLE summary).

85 Rosi, A., Mena, P., Pellegrini, N., Turroni, S., Neviani, E., Ferrocino, I., Di Cagno, R., Ruini, L., Ciati, R., Angelino, D. and Maddock, J. (2017), Environmental impact of omnivorous, ovo-lacto-vegetarian, and vegan diet. *Scientific reports*, 7(1), pp.1-9.

86 Reinhardt, S.L., Boehm, R., Blackstone, N.T., El-Abbadi, N.H., McNally Brandow, J.S., Taylor, S.F. and DeLonge, M.S. (2020), Systematic review of dietary patterns and sustainability in the United States. *Advances in Nutrition*, 11(4), pp.1016-1031 (TABLE summary).

87 Lacour, C., Seconda, L., Allès, B., Hercberg, S., Langevin, B., Pointereau, P., Lairon, D., Baudry, J. and Kesse-Guyot, E. (2018), Environmental impacts of plant-based diets: how does organic food consumption contribute to environmental sustainability? Frontiers in nutrition, p.8.

88 For example, Peters, C.J., Picardy, J., Darrouzet-Nardi, A.F., Wilkins, J.L., Griffin, T.S. and Fick, G.W. (2016), Carrying capacity of US agricultural land: Ten diet scenarios. *Elementa: Science of the Anthropocene*, 4 (TABLE summary). See in particular Figure 2.

89 Alexander, P., Brown, C., Arneth, A., Finnigan, J. and Rounsevell, M.D. (2016), Human appropriation of land for food: The role of diet. *Global Environmental Change*, 41, pp.88-98.

90 Röös, E., Bajželj, B., Smith, P., Patel, M., Little, D. and Garnett, T. (2017), Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. *Global Environmental Change*, 47, pp.1-12 (TABLE summary).

91 Poore, J. and Nemecek, T. (2018), Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392), pp.987-992. See section "Mitigation through consumers" and figure S14.

92 Poore, J. and Nemecek, T. (2018), Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392), pp.987-992.

93 Peters, C.J., Picardy, J., Darrouzet-Nardi, A.F., Wilkins, J.L., Griffin, T.S. and Fick, G.W. (2016), Carrying capacity of US agricultural land: Ten diet scenarios. *Elementa: Science of the Anthropocene*, 4 (TABLE summary), the scope of which is the United States rather than global.

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These land use patterns are important because stakeholders often disagree on the relative harms and benefits of different types of cropping, grazing and rewilding practices, and therefore on the extent to which, if at all, we should reduce animal-sourced food consumption, particularly in richer countries.

The reductions in pasture and arable land use that could theoretically be achieved by a shift to diets lower in animal products are often interpreted as beneficial, particularly by those who call for extensive **rewilding** to restore damaged native ecosystems, such as forests or species-rich grasslands. Another argued benefit is that the shift could reduce direct agricultural emissions at the same time as sequestering large amounts of carbon in ecologically appropriate vegetation[94].

Others see a large reduction in pasture area as environmentally undesirable or unnecessary, arguing that (as discussed above) extensive grazing is beneficial to soil health, soil carbon and on-farm biodiversity.

There is also concern about the impacts of crop production itself (both for food and for feed), based as it often is today on crop monocultures, ploughing, and biocide use. The argument is that crop cultivation is inherently harmful to the soil, causing both soil erosion and a reduction in soil biodiversity, both of which have potentially negative long-term effects on yields and food security. Although this critique is sometimes used to argue against plant-heavy diets, a counterargument is that (as shown above) low-meat diets could reduce the area of land that is cultivated for crops. The extent to which dietary change affects demand for both pasture and arable land is likely to depend on whether it is grazed or crop-fed livestock, or both, for which production falls.

Another response to concerns about the impacts of arable farming is to promote alternative systems of production such as organic farming, with or without[95] the use of animal inputs such as manure. The intensive-extensive debate seen with livestock also comes into play here: while organic farming could eliminate synthetic pesticide use and benefit on-farm biodiversity, organic yields are often lower per unit of land area than on conventional farms[96]. This means that unless there is a reduction in demand for crops (for example through dietary change away from crop-fed livestock, or by cutting food waste), the area put to arable farming would have to expand in an all-organic scenario, with harmful effects on both biodiversity and soil carbon stocks in the converted land. **No-till farming**, which aims to alleviate soil erosion, comes with its own set of trade-offs including often higher herbicide or pesticide use and inconsistent findings as to its effects on soil carbon storage[97,98].

A conclusion that many draw is that a reduction in animal-source food consumption (but not a complete shift to veganism) enables the possibility of centring food systems around grass-fed livestock and mixed farming systems where crops, grazing and fallow periods are alternated on the same area of land[99]. It is argued that this kind of

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94 Sun, Z., Scherer, L., Tukker, A., Spawn-Lee, S.A., Bruckner, M., Gibbs, H.K. and Behrens, P. (2022), Dietary change in high-income nations alone can lead to substantial double climate dividend. *Nature Food*, 3(1), pp.29-37 (TABLE summary).

95 See the Vegan Organic Network for advocacy for "stockfree" farming systems.

96 van Der Werf, H.M., Knudsen, M.T. and Cederberg, C. (2020), Towards better representation of organic agriculture in life cycle assessment. *Nature Sustainability*, 3(6), pp.419-425 (TABLE summary). See also the TABLE blog Pépin, A. and van der Werf, H. (2022), Beyond the label: assessing the spectrum of practices in French organic vegetable farming.

97 Jordon, M.W., Willis, K.J., Bürkner, P.C., Haddaway, N.R., Smith, P. and Petrokofsky, G. (2022), Temperate Regenerative Agriculture practices increase soil carbon but not crop yield—a meta-analysis. *Environmental Research Letters*, 17(9), p.093001.

98 Cai, A., Han, T., Ren, T., Sanderman, J., Rui, Y., Wang, B., Smith, P. and Xu, M. (2022), Declines in soil carbon storage under no tillage can be alleviated in the long run. *Geoderma*, 425, p.116028.

99 Examples of a reduction in meat consumption being promoted by commenters who see some role for livestock (in the context of the UK) include: Miers, T. (2022), Eating meat isn't a crime against the planet – if it's done right, The Guardian ("We need to change our diets. We do have to eat significantly less meat."); the Sustainable Food Trust's 2022 report Feeding Britain from the Ground Up (TABLE summary), which models a nationwide shift to consuming slightly less beef and lamb, significantly less poultry, eggs and pork, about a third less dairy, and significantly more pulses than today; Food, Farming & Countryside Commission (2021), Farming for Change: mapping a route to 2030, which says "With major dietary change, an agroecological future for the UK is possible" and assumes a shift towards more vegetables, less sugar and less meat (with up to 35 grams out of a daily protein intake of 50 grams coming from animal sources); and the 2021 report National Food Strategy Independent Review: The Plan (TABLE summary), which recommends a 30% reduction in meat intake by 2032.

low-meat omnivorous way of eating can yield greater environmental benefits than one that is fully vegan because of its ability to harness the nutrient recycling functions of livestock as well as their ability (particularly in the case of ruminants) to convert non-human edible food (such as grass) into foods that humans can eat (meat and milk).

Another land-use issue linked to plant-based diets relates to soy, which is frequently used in plant-based meat analogues because of its high protein content. Some critics argue that since soy is linked to deforestation, eating soy-based foods is therefore unsustainable. However, at least in the UK, soy imported from South America – a hotspot for deforestation – tends to be genetically modified and is therefore unlikely to be consumed directly by humans, because of GM labelling requirements[100]. Globally, the vast majority (77%) of soy is used for livestock feed[101]. Another critique is that consuming soy makes diets reliant on global supply chains instead of utilising locally produced foods (in countries where soy is not grown). One response has been to encourage production of and demand for domestic pulses for food[102] and for feed[103], although there may in some cases be trade-offs between local production and yields, depending on the pulses being grown, the climate, and the other crops which would be displaced.

The human health impacts of plant-based foods and diets

While results are often conflicting, some studies show that vegetarian or vegan diets are associated with lower all-cause mortality than omnivorous diets[104]. They are also associated with some specific health benefits (such as lower risk of cancer[105] and cardiovascular disease[106]), and also with some health drawbacks (e.g. higher risk of bone fractures[107], iron deficiency anaemia and possibly stroke[108]).

Health impacts are often at the heart of concerns about the ingredients in plant-based analogues. Many highly processed plant-based meat alternatives are higher in salt and lower in protein than similar meat products, according to one study, but lower in energy density, total fat and saturated fat, and higher in fibre; and hence, according to the study's authors, healthier overall than meat[109]. Another study found that the composition of both meat and plant-based meat analogues is so variable that no broad conclusions can be drawn about which is healthier[110]. Wider concerns about the contested category of **ultra-processed foods**, which some plant-based analogues fall

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100 See the TABLE blog Fraanje, W. (2020), Soy in the UK: What are its uses?

101 Fraanje, W. and Garnett, T. (2020), Soy: food, feed, and land use change. Food Climate Research Network, University of Oxford.

102 See The Hodmedod Story - Hodmedod's British Wholefoods for an example of a business seeking to increase British production of pulses for food.

103 See The Donau Soja Organisation.

104 Orlich, M.J., Singh, P.N., Sabaté, J., Jaceldo-Siegl, K., Fan, J. and Knutsen, S. (2013), Vegetarian Dietary Patterns and Mortality in Adventist Health Study 2. *JAMA Internal Medicine*, 173 (13), 1230 (TABLE summary).

105 Watling, C.Z., Schmidt, J.A., Dunneram, Y., Tong, T.Y., Kelly, R.K., Knuppel, A., Travis, R.C., Key, T.J. and Perez-Cornago, A. (2022), Risk of cancer in regular and low meat-eaters, fish-eaters, and vegetarians: a prospective analysis of UK Biobank participants. *BMC Medicine*, 20(73). (TABLE summary).

106 Kim, H., Caulfield, L.E., Garcia-Larsen, V., Steffen, L.M., Coresh, J. and Rebholz, C.M. (2019), Plant-based diets are associated with a lower risk of incident cardiovascular disease, cardiovascular disease mortality, and all-cause mortality in a general population of middle-aged adults. *Journal of the American Heart Association*, 8(16), p.e012865. The paper defines cardiovascular disease as a composite measure of coronary heart disease, stroke, and heart failure.

107 Tong, T.Y., Appleby, P.N., Armstrong, M.E., Fensom, G.K., Knuppel, A., Papier, K., Perez-Cornago, A., Travis, R.C. and Key, T.J., 2020. Vegetarian and vegan diets and risks of total and site-specific fractures: results from the prospective EPIC-Oxford study. *BMC Medicine*, 18(1), pp.1-15 (TABLE summary).

108 Livestock, Environment and People (LEAP) programme, Meat, dairy and health: are vegan diets OK, and is too much meat bad? University of Oxford.

109 Alessandrini, R., Brown, M.K., Pombo-Rodrigues, S., Bhageerutty, S., He, F.J. and MacGregor, G.A. (2021), Nutritional quality of plant-based meat products available in the UK: a cross-sectional survey. *Nutrients*, 13(12), p.4225.

110 Bohrer, B.M. (2019), An investigation of the formulation and nutritional composition of modern meat analogue products. *Food Science and Human Wellness*, 8(4), pp.320-329 (TABLE summary).

into (as do many processed meat and dairy products), include that they contain additives, are often designed to be "hyperpalatable" and hence are easily overconsumed, are linked to weight gain[111], are marketed in ways that that encourage their overconsumption, and have been associated with higher cancer incidence and mortality[112].

Highly processed plant-based analogues attract certain criticisms that are not usually applied to traditional vegetarian foods such as beans, for example in relation to large corporations buying and marketing plant-based brands[113]. However, this same appeal is also seen by others as necessary to make plant-rich diets mainstream, easy and appealing, since diets based primarily on relatively unprocessed sources such as pulses and nuts have not achieved mainstream popularity[114].

One concern around marketing is that consumers might not realise how nutritionally different some analogues are to their animal-sourced equivalent. One particularly notable example is vegan cheese, which is often made from coconut oil or potato starch and hence can be low in protein compared to dairy cheese – although versions made from nuts are higher in protein (albeit more expensive). In another example, non-haem iron (the form found in plants) is less bioavailable, i.e. less absorbable by the human body, than haem iron (the form found in meat)[115]. Livestock industries have consequently lobbied against labelling plant-based alternatives as "meat", "milk" and so on. One counterpoint from advocates of plant-based alternatives is that the food industry already uses many names that customers know not to interpret literally, e.g. hot dog, Easter egg, peanut butter, fish finger and so forth. Some plant-rich diets require additional supplementation to be healthy, e.g. vitamin B12 should be added to vegan diets. Many plant-based brands are therefore fortified (e.g. calcium in soy milk, iron in plant-based bacon). Fortification and supplementation are contested practices, having both benefits and drawbacks for individuals and populations – see for example the debate around iodine fortification[116].

Cells

Finally, emerging forms of food production use relatively new technologies based on cells and microbes (including fungi, bacteria or algae). These include cellular agriculture, precision fermentation and production of microbial biomass in bioreactors. These methods differ from traditional fermentation (e.g. beer, bread, kimchi) in several ways.

Cellular agriculture

Cellular agriculture generally refers to growing animal cells in the laboratory (or, once production is scaled up, in a factory). The first lab-grown burger was presented to the world[117] in 2013, and the field has since taken off with many startups working on different types of meat and fish. As of the time of writing (March 2023), meat from cellular agriculture is only available for sale in one place: Singapore, where GOOD Meat, subsidiary of US-based company Eat

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111 Hall, K.D., Ayuketah, A., Brychta, R., Walter, P.J., Yang, S. and Zhou, M. (2019), Clinical and Translational Report ultra-processed diets cause excess calorie intake and weight gain: an inpatient randomized controlled trial of ad libitum food intake. *Cell Metabolism*, 30(1), pp.1-11 (TABLE summary).

112 Chang, K., Gunter, M.J., Rauber, F., Levy, R.B., Huybrechts, I., Kliemann, N., Millett, C. and Vamos, E.P. (2023), Ultra-processed food consumption, cancer risk and cancer mortality: a large-scale prospective analysis within the UK Biobank. *Eclinicalmedicine*, 56, 101840 (TABLE summary).

113 See for example the TABLE Letterbox series Depolarising the future of protein with Garrett Broad and Phil Howard.

114 See for example the Plant-based meat 2021 Resource guide by The Good Food Institute.

115 Bryngelsson, S., Moshtaghian, H., Bianchi, M. and Hallström, E. (2022). Nutritional assessment of plant-based meat analogues on the Swedish market. *International Journal of Food Sciences and Nutrition*, 73(7), pp.889-901.

116 British Dietetic Association (2021), Iodine: The debate around fortification.

117 BBC News (2013), World's first lab-grown burger is eaten in London.

Just, has sold lab-grown chicken at selected outlets[118].

According to an early study (from 2011), the environmental performance of cellular agriculture could theoretically be very good, offering significant reductions in energy use, carbon footprint and water use relative to beef, as well as a 99% reduction in land use[119]. However, since very few commercial processes are yet operating at scale, it is unclear to what extent this potential can be realised in practice. More recent studies, making different assumptions about the bioreactors and sources of nutrients, give a very wide range[120] of carbon and land footprints for cultured meat, some many times higher than those calculated in the 2011 study, as well as impacts that are higher than beef in some other environmental impact categories..

A key contributor to cultured meat's environmental impact is the source of the energy used to run and clean the bioreactors, sterilise the water used and produce the feedstock. Using renewable energy can significantly cut cultured meat's impact compared to using the current UK electricity mix[121]. However, cultured meat's high energy use could mean that its emissions would be mostly carbon dioxide, and hence that it could contribute to ongoing climate warming. In contrast, cattle systems would have an initially high climate impact that would taper off over time, because of the large contribution of methane to their emissions[122]. There is also debate around whether cultured meat would be a good use of limited supplies of renewable energy, compared to other potential users, such as the transport sector.

Another key challenge, in the process of being addressed, is that animal serums are often used in the liquid in which the cells grow (growth media). These are non-vegetarian, ethically contentious[123] ingredients which present a production bottleneck due to limited global supply and also, because of their variability between batches, can make the outcomes of cell culture processes difficult to reproduce.

Precision fermentation

Precision fermentation is the production of certain molecules by genetically modified microbes, such as yeast, grown in a bioreactor. This process has been widely used for decades, particularly in the medical field (e.g. to produce insulin and vaccines) but also to produce food ingredients such as rennet, vitamins for supplements, and vanilla flavouring[124]. Although the process (usually) uses genetic modification, the end product is molecularly identical to the "natural" product. (Note that some companies use marketing copy that glosses over the fact that genetically modified organisms are involved in the process – possibly because of the controversies around genetic modification.) New startups are repurposing[125] the technology to produce haem[126] (to give plant-based food a meaty flavour), egg

118 See TABLE (2020), Cultured meat approved for sale for the first time. See also TABLE (2022), Cultivated meat moves one step closer to sale in the US.

119 Tuomisto, H.L. and Teixeira de Mattos, M.J. (2011), Environmental impacts of cultured meat production. *Environmental science & technology*, 45(14), pp.6117-6123.

120 See Table 5 and Figure 6 of Tuomisto, H.L., Allan, S.J. and Ellis, M.J. (2022), Prospective life cycle assessment of a bioprocess design for cultured meat production in hollow fiber bioreactors. *Science of the Total Environment*, 851(1), p.158051.

121 See Figure 6 of Tuomisto et al. (2022).

122 Lynch, J. and Pierrehumbert, R. (2019), Climate impacts of cultured meat and beef cattle. *Frontiers in sustainable food systems*, 3. (TABLE summary).

123 van der Valk, J. (2022), Fetal bovine serum—A cell culture dilemma. Science, 375(6577), pp.143-144.

124 Figueiras, S. (2022), You're Already Eating Foods With Ingredients Made Using Precision Fermentation, So Why The Fuss About Animal-Free Dairy? Green Queen.

125 Gyr, A. (2022), 2021 State of the Industry Report – Fermentation: Meat, seafood, eggs, and dairy, The Good Food Institute.

126 See Impossible Foods, Heme + The Science Behind Impossible™.

whites[127] and dairy proteins, now commercially available in the form of milk, ice cream and more[128]. Some companies disclose their environmental impacts, for example Perfect Day's whey protein reduces blue water consumption by 96-99%, non-renewable energy use by 29-60% and greenhouse gas emissions by 91-97% relative to the dairy version[129].

Microbial biomass

One example of edible microbial biomass is Quorn – a high-protein food made from the fungus *Fusarium venenatum* – which offers savings in carbon footprint and land use relative to similar animal-sourced products[130]. Another example is nutritional yeast[131]. The feedstock for these products can be sourced from crops such as sugar beet[132].

An emerging technology, still at the very early stages of development, uses an alternative feedstock generated from water and atmospheric carbon dioxide with renewable energy, which then feeds bacteria which can be processed into protein-rich flours. While there may be significant consumer resistance – note also that bacteria have to be processed carefully to remove inedible nucleic acids – this process could potentially feed many more people per hectare than soybeans[133]. Price remains a barrier, however, and the issue of whether this process is a good use of limited supplies of renewable energy also arises.

Shared hopes and concerns

People's values shape the conclusions that they draw about all these novel cell-based food production techniques. For example, those who are wary of the potential unknown downsides of emerging technologies or a have preference for well-established food production techniques might feel that cell-based foods are risky, unnatural or even disgusting. Aesthetic or ideological preferences for "natural" foods or farming methods can also feed into opposition to high-tech food production methods.

Critics of corporate power may worry that a shift towards high-tech food production will further exacerbate existing trends towards concentration and furthermore miss out on the chance to transform the food system to promote equality and justice at the same time as making it more environmentally sustainable. The perceived risk is that food supply chains will remain or become increasingly dependent on just a few companies that use proprietary processes, that may not offer full transparency as to the environmental impacts of their products, whose economic power may prevent the emergence of alternative business models or visions for the future of food, and whose marketing may continue to promote "Western" foods and diets at the expense of local food cultures. Many of these concerns already apply to highly processed animal-sourced foods as well as to general agricultural inputs such as seeds and fertilisers. There is also concern about food production becoming dependent on highly complex, global and fragile technology supply chains – again, this critique already applies to much of the modern world, including high-tech tractors, trucks, industrial processes and so forth used to produce, process and transport livestock, crops and

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127 See The EVERY Company Makes Vegan Egg Protein Via Fermentation.

128 See a list of products using the whey protein made by Perfect Day here: Partners Using Perfect Day Dairy Protein.

129 See Perfect Day (2021), The Life Cycle of Our Non Animal Protein. The original life cycle assessment by WSP can be downloaded here.

130 Carbon Trust (2022), Quorn Footprint Comparison Report.

131 A high-protein flaked or powdered product used as a cooking ingredient or condiment and commonly available in supermarkets.

132 Smetana, S., Mathys, A., Knoch, A. and Heinz, V. (2015), Meat alternatives: Life cycle analysis of most known meat alternatives. The International Journal of Life Cycle Assessment, 20, pp.1254-1267.

133 Leger, D., Matassa, S., Noor, E., Shepon, A., Milo, R. and Bar-Even, A. (2021), Photovoltaic-driven microbial protein production can use land and sunlight more efficiently than conventional crops. *Proceedings of the National Academy of Sciences*, 118(26), e2015025118 (TABLE summary).

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agricultural inputs.

Advocates of precision fermentation and other cell-based food production methods argue that they could produce an abundance of foods with much lower impacts on the environment, freeing up large tracts of land to restore native ecosystems; that their products could be tailored to individual nutritional requirements and potentially be even healthier than the livestock versions; and that they can be appealing to consumers, perhaps more so than traditional plant-based foods. This conclusion is compatible with a worldview that sees a need for us to minimise our footprint on landscapes and restore nature, even if by doing so we use "less natural" forms of food production; and that it is feasible for consumers to switch to cell-based products, for example because some of them (e.g. dairy proteins) can be functionally identical to the livestock-derived versions.

Conclusion

The future of food systems is highly contested, and the role of livestock and its alternatives particularly so. The polarisation of public discourse makes it difficult to tease out what is fact, what are legitimately differing interpretations of the same evidence, and which narratives either contradict the available evidence or rely on assumptions that have not yet been verified scientifically. While it is beyond the scope of this briefing paper to definitively settle the debates around livestock, the following rough clusters indicate areas where there is more and where there is less certainty.

There are several areas where there is a reasonably well-established scientific consensus. These include:

- **For any given food type, there is a wide range in environmental performance** between different farms, agricultural practices and locations. Furthermore, broad categories of food include a variety of products with highly varied impacts. For example, "seafood" includes both overfished species and lower-impact options such as unfed bivalve aquaculture, and "ruminant meat" production encompasses cattle grazing on recently deforested land, those in intensive feedlot systems, as well as those reared in grazing systems that are designed to enhance soil health and on-farm biodiversity. Estimates of the environmental impacts of novel technologies such as cellular agriculture are also wide, partly because the technology is not yet fully developed.

- ***Current* global average carbon footprints and land use per gram of protein** (as opposed to future potential impacts if different production systems were adopted) tend to be highest for ruminant meat, moderate for other animal products and lowest for plant-based sources of protein. This pattern holds true whether short-lived methane is included or excluded from calculations. The fact that there are some exceptions to this rule of thumb, as well as a great range in impacts between farms, does not invalidate the general pattern in global average impacts.

- On average**, ruminants need more feed than monogastrics** to produce a kilogram of meat, and intensive systems require less feed than extensive systems. The trade-off is that ruminants can and do make greater use of human-inedible feedstuffs such as grass, especially those in extensive systems, and hence can in some circumstances add to the global supply of edible protein. Intensive systems, particularly for monogastrics, rely more on human-edible feeds such as grains and soy and hence consume a large part of the global supply of edible protein.

- There is a high degree of agreement among researchers and many other stakeholders on **the environmental benefits of reducing animal-sourced food consumption**, albeit not to zero, particularly in countries (primarily richer ones) where people already eat a lot of animal products. In addition to the lower average greenhouse gas emissions of plant-based foods compared to animal-sourced foods, these benefits are largely because diets lower in animal products than today's diets would notably decrease grazing land use and also decrease arable land use, freeing up land that could potentially be used to restore ecosystems.

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- **Primarily plant-based diets have both some health benefits and some health drawbacks** compared to omnivorous diets with higher levels of animal products. (Primarily) plant-based diets include both those that are the default because of the constraints of poverty and those that are voluntarily adopted for environmental, ethical or health reasons, and their health implications depend on this context as well as the broader lifestyles of the individuals concerned.

For several issues, disagreements arise largely because of differing interpretations of established evidence. These include:

- **The importance of different metrics for measuring the impacts of different production methods**. Choices of metrics may sometimes depend on which impacts are deemed to have the most global importance, or else on the aspects for which a given production system offers the most benefits. For example, the frequent focus on carbon footprint and land use is partly because these impact categories are arguably among the most significant ways in which the food system contributes to the global environmental crisis. However, a focus primarily on these two metrics, at the possible expense of other metrics, has been criticised as being too narrow. Less intensive systems, such as organic crop farming, may perform better on other metrics, such as pollinator and soil health. Advocates of "regenerative" farming systems often argue that it is important to focus more holistically on impacts and their interactions across many issues, such as biodiversity and livelihoods.
- **The interpretation of GWP* as a measure of methane's climate impact**. Stakeholders who hold the same scientific understanding of the concept can nevertheless come to differing conclusions as to the implications for society. Some argue that GWP* shows that some stable or slowly decreasing level of ruminant production is compatible with net zero targets in addition to providing wider benefits for society. Others argue that GWP* makes clear the large short-term climate mitigation opportunity offered by rapidly reducing ruminant production, with co-benefits for nature restoration.
- **The benefits and drawbacks of feeding edible crops such as grains and soy to livestock**. The practice tends to be seen as more beneficial by those who place more weight on meeting demand for animal products (as opposed to shifting diets towards plants), reducing land use (relative to extensive grazing), or maintaining what they may see as the higher welfare standards of enclosed livestock farms. In contrast, it tends to be seen as more detrimental by those who prioritise reducing arable land use (including deforestation to grow soy), maximising the quantity of food of any type available to people (by freeing up crops for direct consumption, which could provide more calories and protein than animal-sourced foods from the livestock they would have fed), and ceasing feedlot-style livestock production (for example because of animal welfare concerns, or because they believe grass-fed livestock produce healthier foods).
- **Whether the potential for reforestation or other native biomass restoration should be included in reported carbon footprints of food**. The debate here arises largely because of different opinions on what should be included when calculating impacts. The choice of counterfactual scenario against which to compare current impacts may depend on judgements about the importance of alternative paths of action – for instance, the "carbon opportunity cost" methodology compares current food production to potential reforestation because of the perceived benefits of that strategy for both climate and nature.
- **The importance or otherwise of animal rights and animal welfare**. Conclusions here may depend on the actions that an individual may deem morally unacceptable in any circumstances (e.g. killing an animal unnecessarily; causing an animal to suffer during its life; or withholding optimally nutritional foods from people), on balancing the relative importance of ethically acceptable options (e.g. some degree of animal suffering may be accepted as the price for providing animal foods to people; killing animals may be accepted if sufficiently high welfare standards are enforced), and on differing definitions of animal welfare.

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- **The relative societal benefits of traditional farmed landscapes versus those that are partially or completely rewilded**, which influences conclusions about the importance (or otherwise) of reducing the land used by the food system, particularly for grazing.
- **The social, economic and political implications of processed plant-based alternatives and cellular agriculture**. While they have been a flashpoint for debate particularly in relation to alternative proteins, many of the same concerns also apply to current livestock and crop production models.

In some areas, there remains considerable scientific uncertainty. Most notably:

- **The potential of grazing to induce ongoing and permanent soil carbon sequestration** remains in question. People in the regenerative movement, including some farmers, sometimes assume that indefinite build-up of soil (and hence of carbon) is possible and hence see grazing management as a vital climate solution, outweighing the climate impact of the methane and other emissions produced by ruminants. Other stakeholders, including many academic researchers, think that ruminants can induce significant soil carbon sequestration in specific circumstances but that it will eventually plateau after the system reaches capacity in a few decades (the same would be true of reforestation); hence they conclude that grazing can have an important but finite role in climate mitigation. Scientific understanding is still advancing but the societal debate remains unsettled.
- **New food production technologies such as cellular agriculture, precision fermentation and microbial biomass** can theoretically offer large savings in carbon footprint and land use relative to their animal-sourced equivalents in some cases, depending on energy source. However, as many of these technologies are yet to be proven at scale and in practice, life cycle analyses remain speculative in many cases and make assumptions (e.g. about feed source) that may turn out to be inaccurate.

When navigating the messy debates about the future of livestock and its alternatives, it seems unproductive in most cases to treat entire categories of food as wholly good or bad, because there is so much variation in nutritional qualities, environmental impacts, social context and so on. It is important to recognise the clear patterns shown by the data – for example the tendency of plant-based foods to have lower average carbon footprints and land use. However, it is also important to consider the differing sustainability implications of each of the options within each category and consider how to improve the performance of every type of food, whether through reformulating plant-based analogues to be more nutritious, or through improving grazing management to protect soil health. Narratives, values, assumptions and aesthetics all play an important role in influencing how people interpret scientific evidence – sometimes reinforcing existing worldviews. Despite the apparent polarisation of discourse around food, there is room for a wide range of middle-ground options that use a balance of many of the different food production options outlined in this piece.