Animal 15 (2021) 100360

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Animal board invited review: Animal agriculture and alternative meats – learning from past science communication failures

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A R T I C L E I N F O

Article history:
Received 6 June 2021
Revised 18 August 2021
Accepted 23 August 2021

Keywords:
Cultured meat
Environment
Life cycle assessment
Plant-based meat
Sustainable diet

A B S T R A C T

Sustainability discussions bring in multiple competing goals, and the outcomes are often conflicting depending upon which goal is being given credence. The role of livestock in supporting human well-being is especially contentious in discourses around sustainable diets. There is considerable variation in which environmental metrics are measured when describing sustainable diets, although some estimate of the greenhouse gas (**GHG**) emissions of different diets based on varying assumptions is commonplace. A market for animal-free and manufactured food items to substitute for animal source food (**ASF**) has emerged, driven by the high GHG emissions of ASF. Ingredients sourced from plants, and animal cells grown in culture are two approaches employed to produce alternative meats. These can be complemented with ingredients produced using synthetic biology. Alternative meat companies promise to reduce GHG, the land and water used for food production, and reduce or eliminate animal agriculture. Some CEOs have even claimed alternative meats will 'end world hunger'. Rarely do such self-proclamations emanate from scientists, but rather from companies in their efforts to attract venture capital investment and market share. Such declarations are reminiscent of the early days of the biotechnology industry. At that time, special interest groups employed fear-based tactics to effectively turn public opinion against the use of genetic engineering to introduce sustainability traits, like disease resistance and nutrient fortification, into global genetic improvement programs. These same groups have recently turned their sights on the 'unnaturalness' and use of synthetic biology in the production of meat alternatives, leaving agriculturists in a quandary. Much of the rationale behind alternative meats invokes a simplistic narrative, with a primary focus on GHG emissions, ignoring the nutritional attributes and dietary importance of ASF, and livelihoods that are supported by grazing ruminant production systems. Diets with low GHG emissions are often described as sustainable, even though the nutritional, social and economic pillars of sustainability are not considered. Nutritionists, geneticists, and veterinarians have been extremely successful at developing new technologies to reduce the environmental footprint of ASF. Further technological developments are going to be requisite to continuously improve the efficiency of animal source, plant source, and cultured meat production. Perhaps there is an opportunity to collectively communicate how innovations are enabling both alternative- and conventional-meat producers to more sustainably meet future demand. This could counteract the possibility that special interest groups who promulgate misinformation, fear and uncertainty, will hinder the adoption of technological innovations to the ultimate detriment of global food security.

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https://doi.org/10.1016/j.animal.2021.100360
1751-7311/

Implications

Demand for animal source food is rising with increased population and income levels. Animal-free alternatives and manufactured food items that aim to substitute for meat, milk and eggs in the diet are emerging markets. Ingredients sourced from plants and animal cells grown in culture are two approaches employed to produce alternative meats. The relative merits of these products compared to animal products depend upon the comparator metric, the manufacturing system, and the reference animal species. Technological innovations to continuously improve the efficiency of both conventional and alternative food production systems will be requisite to sustainably address global food security demands.

Introduction

The growth in the human population from around three billion in 1960 to 6.8 billion in 2010 was coupled with a four-fold increase in meat production (Smith, 2013). Innovations in production practices (breeding, feeding, and animal care) have contributed to sustained increases in the availability of animal source food (**ASF**) in many countries. Perhaps this is most famously illustrated by the modern broiler industry. Before the discovery of vitamins A and D between 1915 and 1925, it was not possible to grow chickens year-round. Vaccines and biosecurity protocols, and moving animals into secure housing facilities reduced disease exposure and predation. Breeding advances, including hybridization, increased yield and feed efficiency, were spurred by the 'Chicken of Tomorrow Contest' of the late 1940s (Sunde, 2003). In 1957, a 42-d-old broiler weighed 586 g and had a feed conversion ratio (g of feed/g of BW gain) of 2.8; whereas in 2016, a broiler of the same age weighed 2 900 g with a feed conversion ratio under 1.70. Evidence from feeding studies involving heritage-style chicken breeds suggests that although nutrition and management have played a significant role in these changes, it is estimated that improved genetics and breeding accounted for approximately 80–90% of these efficiency gains (Tavárez and Solis de los Santos, 2016). These improvements have dramatically decreased the environmental footprint of a kilogram of chicken protein. Chicken consumption has increased globally since the mid-twentieth century, and in 2019, a staggering 72.1 billion chickens were slaughtered for food (FAO, 2020). Interestingly, consuming chicken was not perceived as 'manly' in the United States, and so in the late 1960s, Frank Perdue and Don Tyson, the two largest poultry producers in the United States, developed a marketing campaign to alter that perception which included television commercials with the slogan 'It takes a tough man to make a tender chicken.' In conjunction with studies from the American Heart Association suggesting negative health effects of red meat, chicken replaced beef as a menu item to become the most consumed terrestrial meat globally, at 132 MMt in 2020. Large-scale shifts in the consumption of ASF, as evidenced by chicken, milk and tilapia, occurred when publicly funded technological innovation was scaled-up by the private sector under supportive policy regimes (Moberg et al., 2021).

There have been many ambiguities and contradictory findings about the health impacts of ASF over the years, especially in dietary recommendations for consumers in middle to high-income countries (**MHIC**), where typical diets often exceed recommended levels of dietary energy and protein. These include conflicting recommendations regarding the healthfulness of eggs (Drouin-Chartier et al., 2020), dairy products in general (Dehghan et al., 2018; Soedamah-Muthu and de Goede, 2018), margarine versus butter (Pimpin et al., 2016), and red meat (Micha et al., 2010; Chen et al., 2013; Abete et al., 2014; Wang et al., 2016; Schwingshackl et al., 2017; Leroy and Cofnas, 2020). In many cases, observational nutritional epidemiology studies suggested a negative impact of ASF, but further studies did not always confirm that association leading to sometimes contradictory messages, and often fierce disagreements even among subject matter experts in the public health scientific literature (Godfray et al., 2018; Klurfeld, 2018; Leroy and Cofnas, 2020). Additionally, since the publication of Livestock's Long Shadow (Steinfeld et al., 2006), there has been an increasing focus on the negative environmental impacts of livestock production. These discussions tend to focus on a few dimensions of intensive livestock systems in the developed world, notably their environmental impacts and the harm to human health that can be caused by high rates of consumption of ASF and zoonotic diseases (Godfray et al., 2018). The other functions of livestock systems such as converting by-products from the food system, crop residues and grass resources into nutrient-dense food providing a valuable source of essential micronutrients, zinc, vitamin A, iron, vitamin B_{12}, riboflavin, and calcium; supporting crop production with manure and draft animal power; providing a regular income, insurance and savings; in addition to fulfilling important cultural, religious and social roles, are often absent or overlooked (Salmon et al., 2020).

These issues have resulted in the development of a market for animal-free alternatives and manufactured food items that aim to be a substitute for ASF in the diet. Ingredients sourced from plants; and animal cells grown in culture are two approaches employed to produce alternative meats. This latter group encompasses products commonly referred to as 'cultured' meat, milk and other animal products. These products can be complemented with ingredients produced using synthetic biology to genetically modify microbes to manufacture specific products, typically by fermentation. To date, alternative meat companies have mostly been located in MHIC (Fig. 1). The framing employed by leading alternative protein stakeholders revolves around five key promissory narratives namely, (1) the promise of being healthier than animal foods by being higher in protein and free from antibiotics; (2) the promise to feed the projected growing global population using less planetary resources; (3) the promise of offering more environmentally efficient production without the need for intensive livestock production or animal slaughter; (4) the promise of increased food safety and traceability via techno-science; and (5) the promise that not only will the alternatives be better for

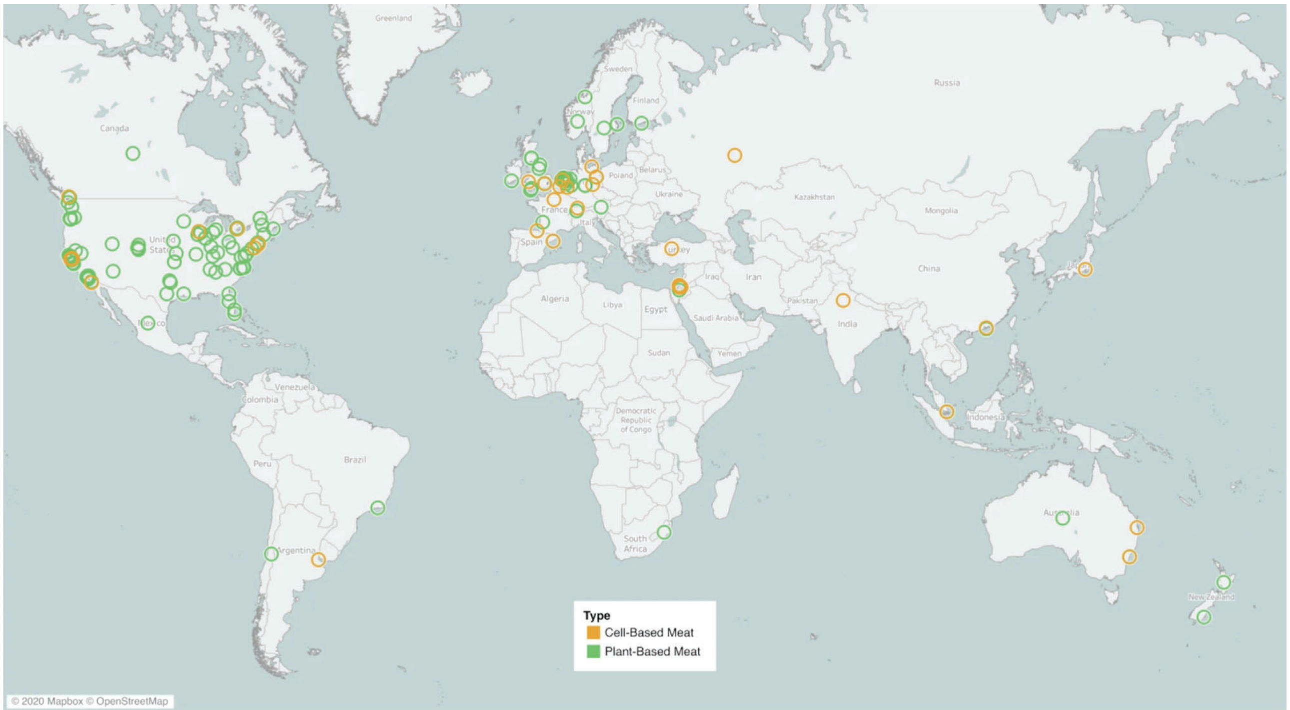

Fig. 1. Geographical distribution of plant-based (green circles) and cell-based (orange circles) alternative meat companies. Companies were listed in the Good Food Institute alternative protein company database (August 2020). Reproduced from Rubio et al. (2020).

humans and the planet but they will also be indistinguishable in taste (Sexton et al., 2019). California-based Impossible Foods even goes so far as to have a mission of completely replacing animals in the food system by 2035, and according to CNN, the Silicon Valley EAT JUST CEO, 'wants to end world hunger' (Mohorčich and Reese, 2019).

Rarely do such hubristic claims emanate from scientists familiar with the complexities of the global food system, but rather from companies, in their efforts to attract venture capital investment and market share (Sexton et al., 2019). Such bold pronouncements are reminiscent of the early days of the biotechnology industry. There too, finance followed aspirations that genetically engineered food 'would alleviate world hunger, create a more sustainable food supply, and create healthier, cheaper food for consumers' (Mohorčich and Reese, 2019). These promises opened the biotechnology industry to attack by activist groups, who effectively created fear around genetically modified organisms (**GMOs**) by framing GMOs as 'unnatural' and therefore unsafe to eat and grow. And while the target of these campaigns was ostensibly multinational companies, the impact was to preclude global access of academic researchers, and developing countries, to the use of agricultural biotechnology. As a result, virtually none of the promises of GMOs to solve major problems in agriculture, nutrition, sustainability, and food security came to pass. Many of these same special interest groups have since moved their 'Frankenfood' sights, a pejorative term for genetically modified food whether it be derived from genetically engineered plants or animals, toward the unnaturalness of cell-cultured meat, and the processed nature of many plant-based meat alternatives. It bears contemplating whether amplifying misinformation or creating fear about any food production method is in the long-term best interests of global food security. Perhaps now is an opportune time to communicate how producers of both alternative and conventional meats are using science and innovation to try to improve the sustainability of their products. And that jointly, rather than vilifying alternative systems, we need to tell compelling stories around how the adoption of innovation in culturally appropriate food production systems worldwide is crucial to global food security. Failure to do so may increase the chances that misinformation, fear, and uncertainty will ultimately preclude access to useful innovations in agriculture and food production globally.

The problem

Currently, plant sources of protein provide the majority of the global protein supply (57%), with meat (18%), dairy (10%), fish and shellfish (6%) and other animal products (9%) making up the remainder. Livestock supply chains are associated with 14.5% of all human-induced greenhouse gas (**GHG**) emissions (Gerber et al., 2013). The emission intensity (amount of GHGs emitted per unit of output produced) of livestock products varies depending upon product, species and environmental factors (Herrero et al., 2013). Protein-based livestock emission intensities range from a high of 404 kg CO_2eq/kg of protein for buffalo to a low of 31 kg CO_2eq/kg protein for eggs (MacLeod et al., 2018). The emission intensities of ASF are higher than protein-rich plant products such as nuts, peas, pulses and groundnut which average 2.6, 4.4, 8.4 and 12.3 CO_2eq/kg protein, respectively (Poore and Nemecek, 2018). Demand for ASF is rising in conjunction with increased population and income levels. These are commonly accepted facts. What to do about this projected ASF demand, and whether this is a good or a bad thing, are where there are major disagreements. The scientific literature reveals a breathtaking array of different metrics being discussed, and varying perspectives. Recognizing that livestock provide multiple benefits in addition to the protein found in milk, meat and eggs adds significant complexity to already complicated and impassioned discussions. There are so many proposed solutions to this increasing demand, and counter narratives being promoted, that this topic has become something of an infodemic, even among scientists. Wikipedia, an online encyclopedia defines infodemic as a blend '*of ''information' and 'epidemic' that typically refers to a rapid and far-reaching spread of* *both accurate and inaccurate information about something, such as a disease. As facts, rumors, and fears mix and disperse, it becomes difficult to learn essential information about an issue.'* And when it comes to the role of ASF on human health and climate change, especially as it relates to GHG emissions, it becomes increasingly murky. Because animal agriculture is immensely varied in its regional practice, impacts, and nutritional importance, it does not lend itself to a simple 'eat this, not that' dichotomous framing. The role of livestock in supporting human well-being is contentious in discourses around sustainable diets. It is close to impossible for non-experts to decipher the nuances of the various metrics being used by different groups, so people seem to be using motivated reasoning to pick the metric that agrees with their belief system and worldview and ignoring the rest. It is recognized that individuals are more likely to accept facts if they either align with the values they hold or reinforce a predisposition (Kahan et al., 2011).

In 2010, a group of international experts proposed the following definition of sustainable diets: 'Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources' (Burlingame and Dernini, 2012). While hard to contest this definition, it is inherently problematic as it involves multiple components that have potentially antagonistic interactions. Which is more important, affordability, nutrition, safety, human or natural resources? Further, it is unclear what metrics should be measured as indicators for some of these components. Reviews of the sustainable diet literature reveal that there is considerable variation in which metrics are measured, although the estimated GHG emissions per unit of food for different diets were by far the most common metric measured; with land, energy, and water use also being frequently assessed (Jones et al., 2016).

A systematic review of the literature about the relative health impacts of diets with reduced GHG emissions revealed highly heterogeneous outcomes. Across all indicators of 'healthiness', 64% of lower GHG emission diets were linked to worse nutritional and health indicators. Reduced saturated fat and salt were often associated with diets low in animal products, but these diets were often also high in sugar and low in essential micronutrients (Payne et al., 2016). Additionally, almost all of the research on sustainable diets has been centered in high-income countries. This is relevant because low- and middle-income countries (**LMICs**) experience very different challenges in terms of malnutrition and food insecurity, as compared to high-income countries. In fact, the diets of most poor households in LMIC are still predominantly plant-based, not necessarily by choice, but because of the high price of nutrient-dense ASF. As such, making sustainability comparisons between meat-based and vegetarian or vegan diets in terms of GHG in the developed world makes little sense in the context of LMIC. For the almost 800 million extremely poor people who live on less than $2/day and subsist on a diet heavily based on starchy plant-based foods, more ASF will be required for sustainable development (Zhang et al., 2016), as ASF provides not only calories but, almost more importantly, the nutrients required for achievement of human development potential (Adesogan et al., 2020).

In 2015, the United Nations proposed a set of 17 global Sustainable Development Goals (SDGs) which comprises 169 targets (UN 2015). There are 14 discrete environmental areas of concern identified in the SDGs including (1) water scarcity, (2) natural resource depletion, (3) urban air quality, (4) ozone depletion, (5) human and ecotoxicity, (6) climate change, (7) marine debris, (8) marine eutrophication, (9) freshwater ecosystem quality, (10) depletion of fish stocks, (11) deforestation, (12) land degradation and desertification, (13) biodiversity loss, and (14) invasive species. In a review of 93 journal articles that reported on the environmental assessments of diets, certain areas of concern, especially GHG emissions, were frequently reported on, but there was less focus on many of the other environmental areas outlined in the SDGs (Ridoutt et al., 2017). These authors noted that there was a disturbing tendency for sustainable diets with lower GHG emissions to be described as healthy diets in the literature. They argue that this framing is inappropriate as the social and economic aspects of sustainability were not evaluated, and further the authors argue that GHG emissions represent only one of many environmental concerns, and that in the context of a complete food system, this metric may not even be the most important environmental concern.

Life cycle assessments

Life cycle assessment (**LCA**) is a widely utilized methodology for both benchmarking and comparing food products and production systems (de Vries and de Boer, 2010; Gerber et al., 2015; Warner, 2019). Modern LCAs follow standards produced by the International Standards Organization (i.e., ISO 14040, 14044, 14046) which set out general principles, framework, and guidelines for life cycle practitioners which helps to standardize LCAs (Sieverding et al., 2020). However, there remains a substantial amount of variability among LCAs, especially those analyzing food products and production systems. Typically, variability comes from the system boundaries set for each LCA, the characterization methods used for each impact category, and emission factors applied to life cycle inventories to determine the final life cycle impacts.

In LCA, the functional unit (**FU**) is the reference base which describes the function of the studied object, thus enabling comparisons between different systems. In comparisons between plant-based and animal-based foods, the environmental impact is often expressed per kilogram of food. This approach has been criticized for favoring foods with a higher water content over nutrient-dense products. Clearly, a kilogram of lettuce is not nutritionally equivalent to a kilogram of meat. Using a FU involving only GHG per kilogram of a food item, or even per kilogram of protein, may lead to the conclusion that plant alternatives are always better than those of animal origin as they do not appropriately account for protein quality, the nutritional density of ASF, or the relative availability of micronutrients. Functional units that relate to the energy content or, more recently, nutritional quality of foods (amounts and shares of various macronutrients and micronutrients) per unit of energy have been proposed to provide more nutritionally relevant comparisons (Doran-Browne et al., 2015). The use of emissions/unit nutrient density allows food products with very different nutritional profiles and water content to be more easily and equitably compared. It may also be more beneficial to consider different protein sources in terms of the additional macro- and micronutrients they provide to humans. Considering nutritional elements may also provide a better estimate of the amount of plant and ASF needed to meet the nutritional requirements of a growing global population (White and Hall, 2017; Liebe et al., 2020). When LCAs are calculated to consider aminoacid composition and nutrient density (e.g., iron, vitamin B12, zinc, retinol, and aminoacids), the footprint of animal foods becomes more similar to plant-based foods because animal foods contain highlevels of essential amino acids and micronutrients (Drewnowski et al., 2015; Tessari et al., 2016).

As with all novel meat and milk alternatives, cell-cultured meat has found a place in the conversation surrounding sustainable diets and their environmental impacts. While cell-cultured meat production has yet to be achieved at scale, there have been a few anticipatory LCAs performed to determine the potential environmental impacts of cell-cultured meat and compare them to other sources of protein (Tuomisto and de Mattos, 2011; Tuomisto et al., 2014; Mattick et al., 2015; Smetana et al., 2015). These stud-

Table 1
Environmental impacts of cell-cultured meat from life cycle assessments.[1]

	GHG Emissions(kg CO_2eq)	Energy Use (MJ)	Water Use (L)	Land Use (m^2)	EP (g PO_4eq)	AP (g SO_2eq)	ODP (μg CFC11eq)
Mattick et al. (2015)	7.5	106	217.02	5.5	7.9	70.2	309
(Best case-worst case)	(3.2–22.3)	(44–316)					
Smetana et al. (2015)	23.9–24.64	290.7–373	–	0.39–0.77	–	–	–
Tuomisto and de Mattos (2011)	1.69–2.66	22.8–38.3	282–651	0.19–0.23	–	–	–
Tuomisto et al. (2014)	2.27–4.38	34.5–60.9	332.5–843.8	0.46–2.82	–	–	–
Sinke and Odegard (2021)	2.5–13.5	147–264	42–56	1.7–1.8	–	–	–
(Best case-worst case)	(2.1–22.6)	(124–445)					

Abbreviations: GHG = greenhouse gas; EP = eutrophication potential; AP = acidification potential; ODP = ozone depletion potential; CFC11 = chlorofluorocarbon-11
[1] Results reported using a functional unit of kg of cell-cultured meat produced.

ies assessed GHG emissions, energy, water, and land use. In addition to these impacts, Mattick et al., 2015 assessed eutrophication, acidification and ozone depletion potentials. They present a wide range in results for each life cycle impact category (Table 1), highlighting the variability in the assumptions that were made as to how cultured meat will actually be produced when it is at commercial scale, as well as inherent variability in LCAs as a whole. A recent prospective LCA on cultivated meat was conducted by the Dutch research and consultancy firm CE Delft and commissioned by the Global Action in the Interest of Animals and The Good Food Institute, which is a non-profit advocacy group working internationally to accelerate alternative protein innovation (Sinke and Odegard, 2021). Although it is not peer-reviewed, it is included here in the interests of completeness (Table 1). The FU in that study was 1 kg of high-protein product (meat cells) and the system boundaries were from cradle to facility gate.

System boundaries set in each study, and assumptions around how cultured meats will be grown (e.g. requirement for growth factors in the culture media) were a primary driver for variability observed in the results. Smetana et al. (2015) performed a 'cradle-to-plate' analysis, accounting for not only the production of cell-cultured meat but also consumer preparation of the meat. The other analyses performed a 'cradle-to-factory gate' analysis in which transportation from factory to consumer and cooking of the product are not included in the analysis. The additional transportation accounted for in Smetana et al. (2015) is in part why greater GHG emissions were reported. While cooking will add to energy use associated with the product, this extra step in the LCA does not fully account for the reported increased energy needs. This is in part because Smetana et al. (2015) included the production of growth factors in their system boundaries. Sinke and Odegard (2021) concluded that the recombinant proteins and growth factors required to grow 1 kg of cultured meat were the main contributors to its carbon footprint. Other studies state that the carbon footprint of this step is insignificant in relation to the entire supply chain and did not include it in their analysis (Tuomisto & de Mattos, 2011). Differences in land use across studies can primarily be attributed to the feedstock and culture inputs that were assumed to have been used to successfully culture meat. Those with higher land-use values utilized corn and soybean as their base feedstock inputs, while lower values utilized cyanobacteria as the base feedstock.

Moving forward with the scaling up of cultured meat production facilities, the source of energy will be a primary area of concern. The environmental impacts of cell-cultured meat will be highly dependent on the source of energy utilized for the production processes and making the ingredients used to feed the cells, and whether these energy sources can be decarbonized (Lynch and Pierrehumbert, 2019). The prospective anticipatory cultured meat LCA reported that 'if renewable energy is used to power cell-cultured meat production, this could reduce global warming impacts by 17%, 52%, and 85–92% versus conventional chicken, pork, and beef production, respectively' (Sinke and Odegard, 2021).

To demonstrate the challenges with comparing results across studies, we performed a literature review of LCAs (and other similar assessments) on the environmental impacts of producing various food protein sources. We present the system boundaries used in 54 analyses (5 cell culture, 11 beef, 3 ground beef, 3 dairy beef, 4 pork, 8 plant, 3 insect, 7 dairy, 3 chicken, 4 egg, and 3 lamb; Table 2) and the impacts calculated per kg of product FU (Fig. 2) for: (A) GHG emissions; (B) land use; (C) water use; (D) energy use; (E) eutrophication potential; and (F) acidification potential. These studies are by no means exhaustive of all the LCAs that have been performed on ASF products, rather they serve as an example of the breadth of LCA related research performed on different protein sources, and the variability across all studies that may result from differing system boundaries. Some trends are obvious and biologically based, for example ruminants produce more GHG than monogastrics due to rumination and require more land as a result of being grazing herbivores. Emission intensities of ruminant milk are typically lower than beef, although the latter's emissions are minimized when fed a high-quality ruminant diet, making it more comparable with milk (Herrero et al., 2013). Production systems in the developed world typically have lower emission intensities than those in developing regions. The results demonstrate wide ranges to some degree for all forms of protein, and illustrate the variation that can occur depending upon the LCA system boundaries and assumptions. On average, cultured meat production appears to produce similar GHG emissions to most other ASF protein sources, with the exception of ruminant meats from extensive systems utilizing low quality forage. Plant products generally have a lower GHG than ASF, which is expected given they are at a lower trophic level. However, this framing is highly influenced by a specific definition of the global warming potential (**GWP**), one that has been increasingly questioned by several authors (Allen et al., 2016; Allen et al., 2018; Cain et al., 2019).

Greenhouse gasses

When considering GHG emissions, LCAs typically use the GWP_{100} metric. This metric is assessed over a 100-year time horizon. By this approach, the global warming potentials of methane (CH_4) and nitrous oxide (N_2O) relative to carbon dioxide (CO_2) are multiplied by 28 and 265, respectively (Myhre et al., 2014). The authors of the Intergovernmental Panel on Climate Change Fifth Assessment Report themselves state that the GWP_{100} climate metric should not be considered to have any special significance. However, GHGs vary in their atmospheric lifetime, and importantly, for ruminant production systems, CH_4 is a short-lived climate pollutant (**SLCP**) with an atmospheric lifetime in the order of only 12 years (Myhre et al., 2014). This has led some researchers to suggest that a new expression of the global warming potential metric, known as GWP* (Allen et al., 2018), should be used to compare the temperature response from a change in rate of emission of SLCPs to the temperature response from a pulse emission of carbon dioxide. The very long-term climate impact of CO_2 is the reason

Table 2
The system boundaries of the studies investigating environmental impacts of various protein sources depicted in Fig. 2.

Study by Protein Source	System Boundaries	Study by Protein Source	System Boundaries
Cell Cultured Meat		*Plant-Based Meat*	
Mattick et al. (2015)	Cradle-to-factory gate (excl. growth factors)	Dettling et al. (2016)	Cradle-to-grave
		Fresán et al. (2019)	Factory gate-to-factory gate (excl. crop production before factory)
Sinke and Odegard (2021)	Cradle-to-factory gate		
Smetana et al. (2015)	Cradle-to-consumption		
Tuomisto and de Mattos (2011)	Cradle-to-factory gate (excl. growth factors, vitamins, and cell culture)	Goldstein et al. (2017)	Cradle-to-farm gate (excl. transport and packaging, preparation, and disposal)
Tuomisto et al. (2014)	Cradle-to-factory gate (excl. growth factors and vitamins)	Heller and Keoleian (2018)	Cradle-to-distribution
		Khan et al. (2019)	Cradle-to-factory gate
Beef [1]		Mejia et al. (2020)	Factory gate-to-factory gate (excl. crop production before factory)
Asem-Hiablie et al. (2019)	Cradle-to-consumption		
Broom (2019)	Cradle-to-slaughter		
Goldstein et al. (2017)	Cradle-to-farm gate (excl. transport and packaging, preparation, and disposal)	Smetana et al. (2015)	Cradle-to-consumption
		Van Mierlo et al. (2017)	Cradle-to-consumption
		Insect-Based Meat	
		Smetana et al. (2015)	Cradle-to-consumption
Murphy et al. (2017)	Cradle-to-farm gate (excl. slaughter)	Smetana et al. (2019)	Cradle-to-factory gate
		Van Mierlo et al. (2017)	Cradle-to-consumption
Nieto et al. (2018)	Cradle-to-farm gate (excl. finish phase)	*Milk*	
		Cederberg et al. (2009)	Cradle-to-retail
Dettling et al. (2016)	Cradle-to-grave	Eide (2002)	Cradle-to-end of life
Khan et al. (2019)	Cradle-to-slaughter	Gerber et al. (2010)	Cradle-to-retail
Rotz et al. (2019)	Cradle-to-farm gate (excl. slaughter)	Guinard et al. (2009)	Cradle-to-end of life
		Naranjo et al. (2020)	Cradle-to-farm gate
Stackhouse-Lawson et al. (2012)	Cradle-to-farm gate (excl. slaughter)	Thoma et al. (2013)	Cradle-to-farm gate (excl. transportation and processing)
Stanley et al. (2018)	Gate-to-gate (finish phase only)		
		Wirsenius et al. (2020)	Cradle-to-farm gate (excl. transportation and processing)
Tichenor et al. (2017)	Cradle-to-farm gate (excl. slaughter)		
Ground Beef [1]		*Chicken*	
Goldstein et al. (2017)	Cradle-to-farm gate (excl. transport and packaging, preparation, and disposal)	Goldstein et al. (2017)	Cradle-to-farm gate (excl. transport and packaging, preparation, and disposal)
Khan et al. (2019)	Cradle-to-factory gate	Dettling et al. (2016)	Cradle-to-grave
Dettling et al. (2016)	Cradle-to-grave	Smetana et al. (2015)	Cradle-to-consumption
Dairy Beef [1]		*Eggs*	
Murphy et al. (2017)	Cradle-to-farm gate (excl. slaughter)	Cederberg et al. (2009)	Cradle-to-retail
		Leinonen et al. (2012)	Cradle-to-farm gate (egg production)
Stackhouse-Lawson et al. (2012)	Cradle-to-farm gate (excl. slaughter)		
		Mollenhorst et al. (2006)	Cradle-to-farm gate (egg production)
Tichenor et al. (2017)	Cradle-to-farm gate (excl. slaughter)		
		Pelletier et al. (2014)	Cradle-to-farm gate (egg production)
Pork			
Dettling et al. (2016)	Cradle-to-grave	Wiedemann and McGahan (2011)	Cradle-to-farm gate (egg production)
Goldstein et al. (2017)	Cradle-to-farm gate (excl. transport and packaging, preparation, and disposal)	Verge et al. (2009)	Cradle-to-farm gate (egg production)
Rudolph et al. (2018)	Farrow-to-finish (excl. slaughter)	*Lamb*	
Wirsenius et al. (2020)	Cradle-to-farm gate (excl. transportation and processing	Dougherty et al. (2019)	Cradle-to-factory gate (excl. consumer)

[1] Beef production includes both ground beef and dairy beef within respective studies; however, both dairy and ground beef have been separated in order to provide further analysis.

why climate stabilization depends on actions to achieve net zero emissions of CO_2. As an example, GHGs from Australian livestock production - beef cattle, sheep meat, chicken meat, pig meat, eggs and milk – were assessed using both GWP_{100} and GWP* metrics from 1990 to 2018. In the case of sheep meat production, the industry was assessed as emitting 10.3 MMt CO_2eq in 2018 using the GWP_{100} metric. However, using the GWP* climate metric, the GHG emission footprint was equivalent to the removal of 2.85 Mt CO_2 in part because of the degradation of historical CH_4 emissions from a larger national sheep flock in the past (Ridoutt, 2021).

These authors make the point that avoiding ASF based on the GWP_{100} metric may result in trading a short-term climate benefit from reducing short-lived CH_4 emissions, with a longer-term problem of increased CO_2 and N_2O emissions, making climate stabilization even more difficult. This has implications for sustainable intensification approaches that decrease the emission intensity of ASF by substituting CO_2 emissions for SLCP. Interventions such as providing supplemental crop-based feed rations may appear to lower GHG using the GWP_{100} metric, but they may actually be substituting a long-lived GHG for a SLCP. Perhaps even more paradoxical with prevailing thought, is that red meats from ruminants may actually outperform meat from monogastric animals (pigs and poultry) when using the GWP* metric due to the latter's reliance on crop-based feed rations. These findings emphasize the impor-

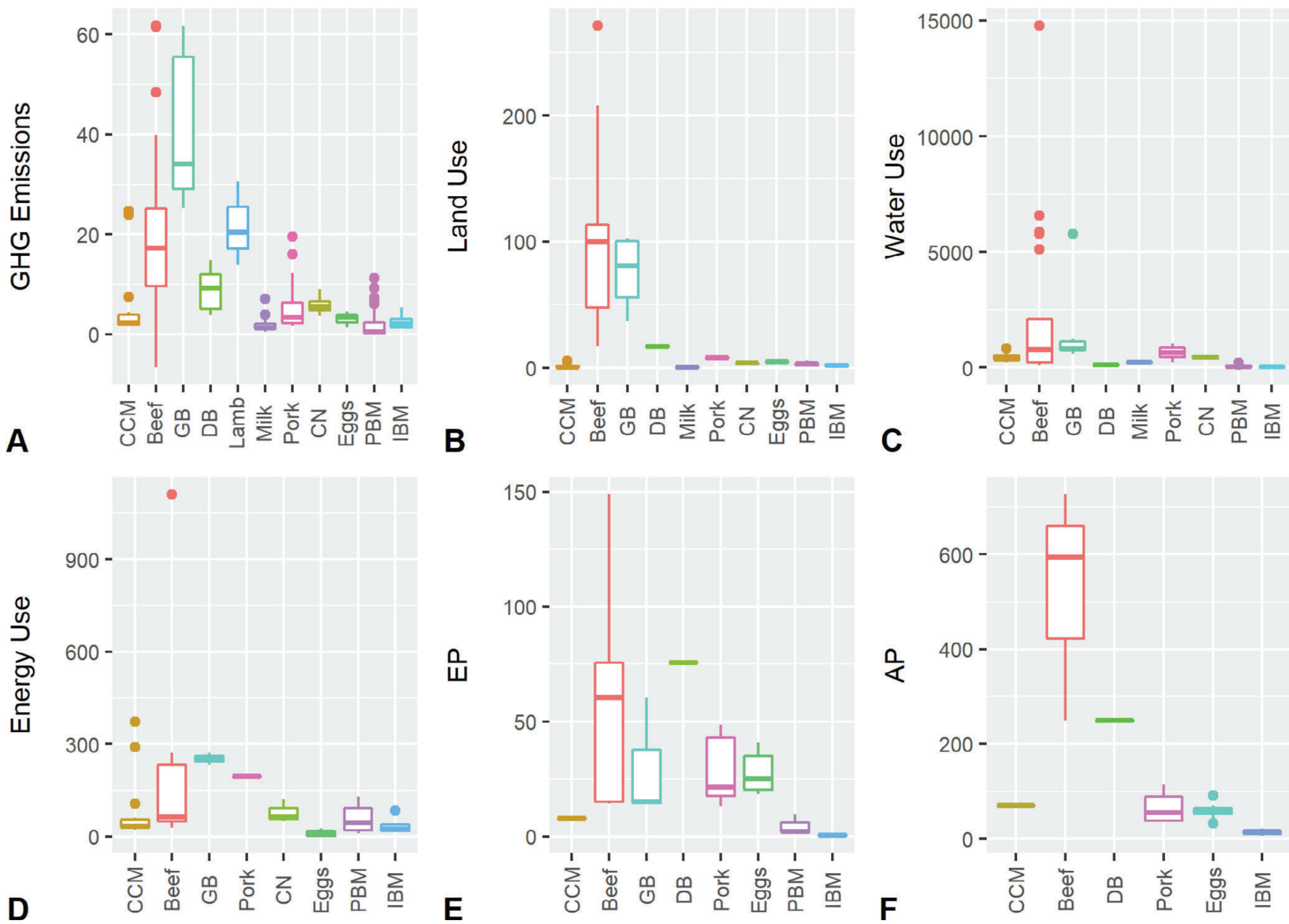

Fig. 2. Life cycle assessment results per kilogram of product for various protein sources[1]. (A) greenhouse gas (GHG) emissions (kg CO_2eq/kg product); (B) land use (m^2/kg product); (C) water use (L/kg product); (D) energy use (MJ/kg product); (E) eutrophication potential (EP; g PO_4e/kg product); and (F) acidification potential (AP; g SO_2e/kg product). All values have been adjusted to a 'per kg product' basis, but data have not been altered to account for other variables (e.g. system boundaries). [1]CCM = cell-cultured meat; GB = ground beef; DB = dairy beef; CN = chicken; PBM = plant-based meat; IBM = insect-based meat.

tance of the choice that even a single climate metric can have on the outcomes and implications of LCA studies.

Additionally, LCAs typically do not consider changes in carbon stocks as it can be a difficult value to accurately obtain and characterize. Land use and land-use change is a large contributor to the GHG balance and within it, soil organic carbon is a major contributor. Soil carbon sequestration has the potential to be a valued sink for GHG emissions. Agricultural practices that influence soil organic carbon by reducing losses or increasing sequestration can play an important role in GHG mitigation. Accumulation rates vary with both climate and agronomic management. The amount of carbon that could be stored by the world's grazing lands is considerable, with estimates ranging from 0.04 to 1.1 Gt CO_2eq/yr (Lal, 2004; Henderson et al., 2015), as a result of improved grazing management (0.148 Gt CO_2eq/yr), and legume sowing (0.147 Gt CO_2eq/yr). These authors warn that the additional ruminant GHG emissions associated with higher forage output are likely to substantially reduce the mitigation potential of these practices, but could contribute to more GHG-efficient livestock production (Henderson et al., 2015). There are several factors that influence whether grazing impacts soil organic carbon including moisture, soil type and carbon saturation levels, and plant species composition (Buckley Biggs and Huntsinger, 2021). Researchers in the soil and range science communities have found the impacts of grazing systems on soil organic carbon to be highly variable. The 2016 technical standard for soil carbon, ISO 14067, prescribes that emissions and removals due to changes of soil organic carbon under ongoing land use should be included in carbon footprints (Sevenster et al., 2020).

Stanley et al. (2018) found that cattle finished on pasture using an adaptive multi-paddock grazing strategy lead to improved soil organic carbon, thereby presenting a situation where beef production produced net negative GHG emissions in a gate to gate finish phase analysis. This means that within the system boundaries set for this analysis, more carbon was sequestered than was emitted. The importance of characterizing carbon sequestration in beef systems was further highlighted in Rowntree et al. (2020), where inclusion of soil organic carbon resulted in a 113% reduction in GWP_{100} (33.55 kg CO_2eq/kg carcass weight to −4.4 kg CO_2eq/kg carcass weight). Similarly, improved soil carbon sequestration was observed for cattle raised in a pasture-based system (Thorbecke and Dettling, 2019) and bison under an adaptive multi-paddock grazing strategy (Hillenbrand et al., 2019). While enteric CH_4 emissions may be increased from pasture raised animals compared to feedlot finished cattle, if carbon sequestration from pasture systems are accounted for, then animal emissions can be offset, resulting in an overall net negative GWP_{100} for specific situations. This offset would be even greater if GWP* was used in the place of GWP_{100}. Recently, the GWP* methodology was used in combination with consideration of the soil organic carbon from associated pastures to examine the 1990–2018 contribution of European dairy small ruminant systems to additional atmosphere warming levels. By this metric, from 1990-2018, the whole European sheep and goat dairy sector did not contribute at all to global warming (Del Prado et al., 2021). In comparison with other protein sources, ruminant production systems present a unique opportunity to have a climate impact consistent with CO_2 removal if herd sizes are decreasing (which degrades historical methane emissions), and soil organic carbon is sequestered. However, it is important to note that carbon sequestration rates can be variable over time depending on factors such as historic use of land, depth, clay content and mineralogy, soil type, water availability, nutrient reserves, landscape position, and the antecedent stock of soil organic carbon (Machmuller et al., 2015; Lal, 2018). It should also be noted that some have criticized the GWP* metric as being unfair because it gives advantages to countries that have had historically high CH_4 emissions (Rogelj and Schleussner, 2019). These authors make an argument that 'applying novel metrics to a predefined policy context is problematic if no appropriate measures are taken to ensure internal consistency with the earlier use of other metrics in that same policy context. In absence of such appropriate measures, policy targets can be re-interpreted without clear scientific or moral reasoning.' This critique can be applied to many of the metrics that are currently being employed to classify sustainable diets.

The Global Livestock Environmental Assessment Model is a modeling framework developed within the Animal Production and Health Division of the Food and Agriculture Organization of the United Nations (**FAO**) (MacLeod et al., 2018). The Global Livestock Environmental Assessment Model uses an LCA approach following guidelines issued by the Intergovernmental Panel on Climate Change, which means that the assessment includes both direct emissions from animals and indirect emissions both upstream and downstream. This approach differentiates key stages within livestock agrifood systems, such as feed production, processing and transport; animal production, animal feeding and manure management; and the processing and transport of products. The Global Livestock Environmental Assessment Model 2 has a base year of 2010 and uses CO_2eq/kg protein calculated as GWP_{100} (Fig. 3). These numbers hide large variations across different production systems. For example, the 295 kg CO_2eq/kg protein average for beef ranges from 93 in feedlot systems to 434 in grassland systems. This reflects different agro-ecological conditions, farming practices and supply chain's management. It is within this gap between high and low emission intensities where opportunities for mitigation can be found. The estimation for mitigation is around 33 percent, or about 2.5 Gt CO_2eq, with respect to the baseline scenario. This figure arises from the assumption that producers in a given system, region and agro-ecological zone would apply the practices of the 10th percentile of producers with the lowest emission intensities, while maintaining constant output. The Global Livestock Environmental Assessment Model 3, currently under development by the FAO with a base year of 2015,

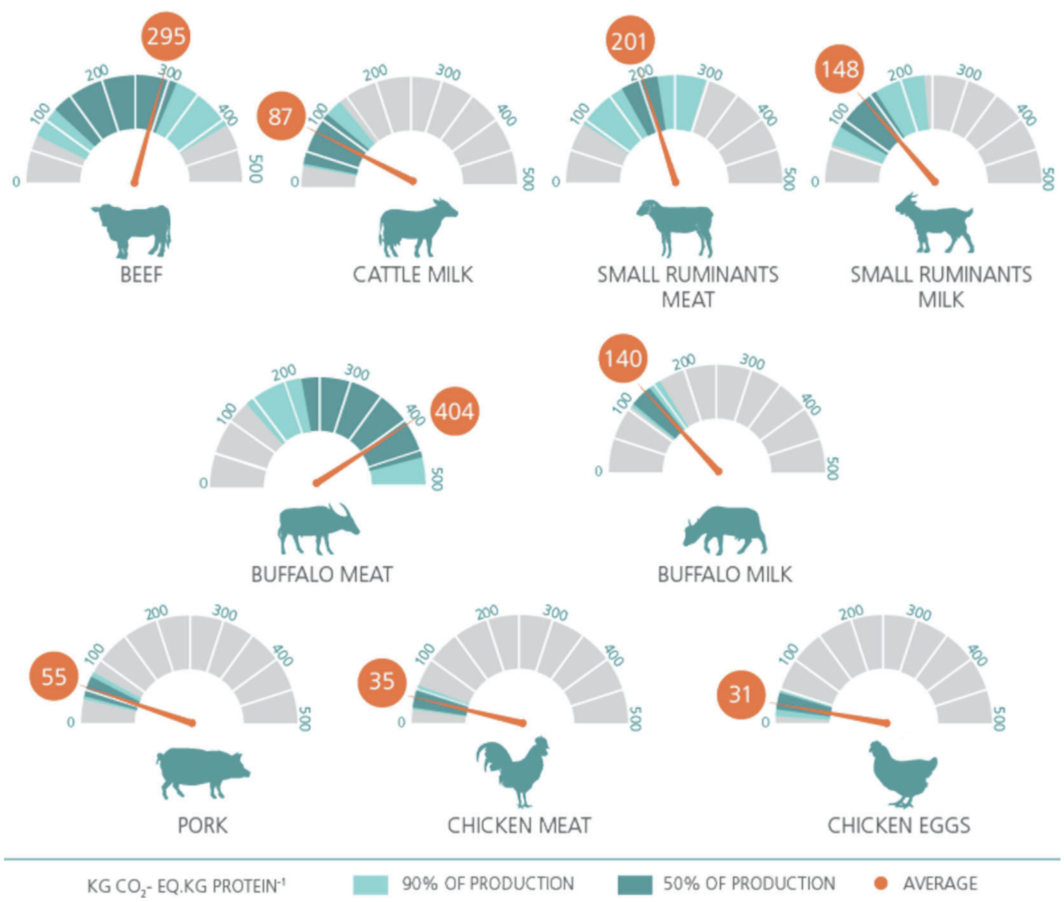

Fig. 3. Global greenhouse gas emission intensities by commodity expressed on a per kg protein basis. Averages (orange) are calculated at global scale and represent an aggregated value across different production systems and agro-ecological zones. Emission intensities vary greatly among producers with 90% of production occurring within the blue-shaded region, and 50% of production occurring within the dark blue bounds. This reflects different agro-ecological conditions, farming practices and supply chain management. It is within this gap between high and low emission intensities that opportunities for mitigation can be found. The estimation for mitigation is around 30%, or about 2.5 Gt CO_2eq if producers in a given system, region and agro-ecological zone were to apply the practices of the 10th percentile of producers with the lowest emission intensities, while maintaining constant output, with respect to the baseline scenario. (GLEAM http://www.fao.org/gleam/results/en; Accessed August 8 2021).

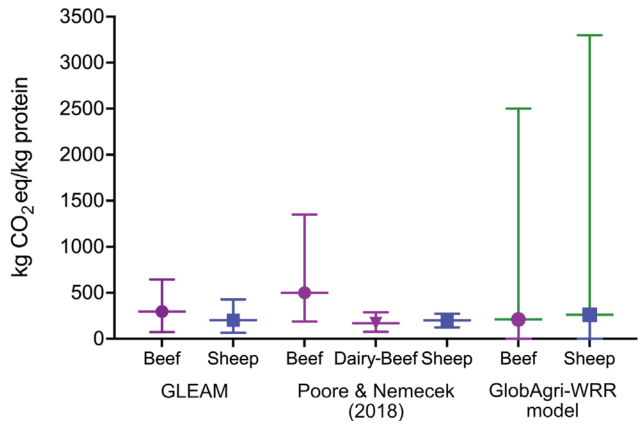

Fig. 4. Greenhouse gas emissions per kg protein for beef (purple) and sheep (blue) meat obtained using three different models. The average and range are shown for the FAO's GLEAM 2.0 life cycle assessment (MacLeod et al., 2018) and for Poore and Nemecek (2018). The GlobAgri-WRR model (Searchinger et al., 2019) provides a single global figure which includes agricultural production (purple circle, blue square for beef and sheep, respectively) plus the opportunity cost of agricultural land-use change (green). Inclusion of this land-use opportunity cost increases this metric by a factor of at least 5-fold relative to the average value of the other two sources for these ruminant sources of protein.

plans to include modules on enhanced accounting of nutrient use and carbon sequestration in livestock systems.

Other groups have developed their own models to arrive at environmental metric estimates. Poore and Nemecek (2018) consolidated data on the multiple environmental impacts of ~38 000 farms producing 40 different agricultural goods around the world in a meta-analysis comparing various types of food production systems. They found that impacts varied 50-fold among producers of the same product, creating substantial mitigation opportunities. They estimated that CO_2eq/kg protein from a beef herd ranges from 202 (10th percentile) to 1 052 (90th percentile), with an average of 499 CO_2eq/kg protein (Fig. 4) which is higher than the numbers calculated by the Global Livestock Environmental Assessment Model 2 (Figs. 3 and 4). Almost all of the variation in this estimate was due to differences in production systems, with the major driver of variance in these numbers being whether arable land was part of the production system. Feeding ruminants with high-energy, low-cellulose feed produced on arable land decreases the emission intensities associated with their milk and meat. The GlobAgri-WRR model from the World Resources Institute (Searchinger et al., 2019) has an estimate of 2 500 kg CO_2eq/kg edible protein for beef, and a whopping 3 300 kg CO_2eq/kg edible protein for lamb (Fig. 4). This model, which is not described in the peer-reviewed literature, includes a statement '*we believe that all or virtually all dry grazing land available in a country is used today, so that increases in grassland areas must come from wetter systems (humid or temperate). We also believe that because dry grazing lands have little alternative use, they would continue to be used even if demand for milk or ruminant meat declined. We therefore program the model so that changes in supply of milk or ruminant meat do not come from increases or decreases in arid grazing systems and instead result in changes in humid and temperate production systems.*' It is therefore assumed that for each additional kg of ruminant protein produced, there is land-use change occurring either directly or indirectly through deforestation elsewhere to replace pasture/cropland. This assumption particularly impacts sheep production, as small ruminants tend to survive in the most arid and least productive landscapes, resulting in large areas of land being required to produce one kg sheep meat. Poore and Nemecek (2018) estimated this number to be an average of 185 ha/ton protein with a range from 24 (5th percentile) to 362 (95th percentile). The assumptions of the GlobAgri-WRR model dramatically increase the GWP_{100} of ruminant source protein as ruminants uniquely occupy grasslands. In this model, ruminant systems are not credited with any soil organic carbon occurring on grazing lands, and irrespective of actual location, they are assigned the opportunity cost of increased emissions from land-use change in humid and temperate production systems. Amortizing projected land-use change to ruminant products violates the system boundaries of the other GHG emission inventories.

These competing metrics are difficult for a non-expert audience to disentangle. If we consider sheep meat production in Australia, as an example, in 2018, the industry produced 1.62 Mt of live weight which generated 784 000 t CO_2; 299 000 t CH_4; and 3 810 t N_2O (Ridoutt, 2021). Using the GWP_{100} metric, the industry therefore produced 10.3 Mt CO_2eq (17.4 kg CO_2eq/kg edible product or ~67 kg CO_2eq/kg protein), equating to a little less than 2% of the country's 2018 emissions. If however, the GWP* metric is used, which considers the degradation of historical methane emissions (Lynch et al., 2020), the industry resulted in a net decrease of 2.85 Mt CO_2eq (-4.80 kg CO_2eq/kg edible product or −18.5 kg CO_2eq/kg protein) (Ridoutt, 2021). Conversely, using the GlobAgri-WRR model that considers the opportunity costs of the sheep being on non-arable grazing land through 2050, the industry produced 151 632 t edible protein (1.62 Mt *0.36 yield of edible product * 0.26 kg protein/kg edible product) which would result in 500 Mt CO_2eq (151 632 t × 3 300 t CO_2eq) (Fig. 4). This equates to around 90% of the entire country's 2018 CO_2eq emissions of 558.4 Mt CO_2eq (GWP_{100})! Other groups have developed estimates of GHG attributable to livestock that include respired CO_2 in GHG emissions (Goodland and Anhang, 2009), an approach that has been criticized as a major deviation from international protocols because the amount of C in feed consumed and CO_2 emitted by livestock are broadly equivalent (Herrero et al., 2011). When there is such variation in the assumptions and system boundaries driving these varying GHG metrics and the time frames they consider, value judgements will be embedded into which metric should be used. This will undoubtedly increase distrust in the figures, and potentially alienate landholders and livestock keepers whose cooperation is needed to adopt GHG mitigation interventions.

Resource use

Total land use is another category where meat alternatives have a lower number than most ASF protein sources (Fig. 2). The total land-use metric does not differentiate between arable and non-arable land. The production of global animal feed requires 2.5 billion ha of land, which is about half of the global agricultural land area. Most of this area, 2 billion ha, is grassland, of which about 1.3 billion ha cannot be converted to cropland. This means that 57% of the land used for feed production is being grazed by ruminant production systems (Mottet et al., 2017). If ruminants were removed from this land, it would produce no human food, and this would impact the livelihoods of millions of smallholder livestock keepers (Mapiye et al., 2020). There is no reason to conclude that food production on non-arable land is less sustainable than food production on well-managed arable cropland, simply because the former achieves lower yields and therefore requires more land use per unit of production. If minimizing total land use is equated to improved sustainability, it leads to the conclusion that food should be intensively produced on the smallest amount of arable land possible. This is actually the model for intensive monogastric animal agriculture systems (poultry and pigs), which are not seen as sustainable by many due to their animal welfare and environmental externalities, and a reliance on the provision of feed grown on arable land that could have been used to grow human food. While it is undoubtedly true that cultured meat facilities will occupy less land than grazing ruminants, the actual environmental and biodiversity benefits that result from that will depend on how the land 'released' from livestock production will be utilized (Stephens et al., 2019; Tuomisto, 2019b).

There are ecosystem services resulting from grazing ruminants that maintain various habitats and species and which are therefore beneficial for biodiversity. The biophysical capacity of land to supply ecosystem services is not considered in LCAs. In the United States, beef cattle ranching actively grazed over 186 million ha in 2017, approximately half of the 363 million ha of total farmland. It is estimated the cumulative economic value of this grazed land use was $24.5 billion; comprised of $17.5 billion for wildlife recreation, $3.8 billion for forage production, and $3.2 billion for other ecosystem services related to the conservation of biodiversity (Maher et al., 2021). Similarly, beef cattle ranching was found to have a positive influence on biodiversity, habitat maintenance, cultural heritage, recreation and tourism in the Canadian prairie provinces of Alberta, Saskatchewan and Manitoba, which collectively support just over 80% of the Canadian beef herd (Pogue et al., 2018). Integrity and productivity of ecosystem goods and services from rangelands are critical to the livelihoods of over a billion people worldwide (Niamir-Fuller and Huber-Sannwald, 2020). Total abandonment of grazing in natural rangelands is likely to be an ineffective climate change policy (Manzano and White, 2019). Food is not the only output of agricultural systems, so life cycle impacts should perhaps be allocated to broader functional units than simply kg of food product to more fully account for the other outputs including rural livelihoods, cultures and landscape services associated with food systems.

Among LCAs, water is commonly characterized as 'green' or 'blue' or a combination of the two, where green water is rainwater and blue water is groundwater and surface water resources (Hoekstra, 2019). While ruminant meat utilizes substantially more water than cell-cultured meat and other proteins, the vast majority of this is green water (Fig. 2). Many studies characterize consumptive water use, where any water, green or blue, removed from stores will not return to the system. Considering water in this regard can become problematic as it does not take into consideration that green water is not in direct competition with water needed for other anthropogenic activities. Green water is inseparable from land, meaning water that falls on one pasture cannot fall on another, and as such it is a proxy land-use indicator. By definition, extensive systems on arid grazing lands will have a large green water footprint, as they occur on large acreages (Damerau et al., 2019). The water is largely returned to the very area where the precipitation fell, through urination, defecation, and respiration. The only green water 'leaving' the system is what is captured in weaned calves when they leave the ranch. Meanwhile, water needed for alternative meat manufacturing systems is blue water. This consumptive water use metric is not ISO compliant (International Organization for Standardization, 2014), as it does not differentiate between water use in regions of water scarcity from that in regions of abundance. It is therefore important to calculate a water scarcity footprint, where each instance of water use in the life cycle of a food product or a diet is multiplied by the relevant local Water Scarcity Index. Recently, the FAO LEAP partnership published their recommendations on water use assessment of livestock production and supply chains (Boulay et al., 2021)

Energy use is variable across all forms of protein sources (Fig. 2). A major factor affecting energy use when comparing these studies is whether or not cooking by the consumer is considered. Many studies end their system boundaries at factory or field gate, thus eliminating any energy needed to transport, store, or cook the protein. While these factors should be relatively similar across all protein sources, it is pertinent to note these distinctions when working to draw conclusions on energy use across studies. While outliers for cell-cultured meat, about half of the data demonstrate that cell-cultured meat has the potential to be the most energy intensive protein. This is in part due to the large amount of energy required to run the bioreactors used to multiply cells. Studies to date only consider the creation of muscle tissue and do not consider additional energy required to create fat cells. Cell-cultured fat manufacturing platforms will require considerable optimization to identify appropriate cell lines, bioprocess strategies, and tissue engineering techniques to achieve simple systems that can cost-effectively scale (Fish et al., 2020).

Eutrophication potential and acidification potential are two LCA characterization factors that are studied less frequently than other factors. In the case of cell-cultured meat, Mattick et al. (2015) is the only study to consider eutrophication potential or acidification potential, making it difficult to make any accurate comparisons to other proteins. In general, animal sourced proteins have greater eutrophication potential and acidification potential than cell-cultured meat or plant-based proteins. Emissions contributing to eutrophication potential and acidification potential in animal protein systems are primarily related to crop production for animal feeds and management of animal manure, respectively (Tichenor et al., 2017). As cell-cultured meat production will not directly require these inputs, it is likely that eutrophication potential and acidification potential will remain lower than animal proteins as production of cell-cultured meat is upscaled. Compared to all meat products, both cultivated and conventional, the environmental metrics and the carbon footprint of plant-based protein products are lower.

Human health and alternative meats

Human health is not typically a metric formally considered in LCAs, and yet this topic is perhaps the most contested literature that comes up in the discussion around alternative meats. Are ASF foods part of a healthy diet, and if so how much is too little or too much? As with the other metrics discussed, motivated reasoning can be used to pick a segment of the scientific literature that supports a particular world view. The EAT-Lancet Commission suggested that 'healthy diets have an appropriate caloric intake and consist of a diversity of plant-based foods, low amounts of animal source foods, unsaturated rather than saturated fats, and small amounts of refined grains, highly processed foods, and added sugars' (Willett et al., 2019). Review papers that identify red and processed meat as an intrinsic cause of chronic diseases based on observational studies (Micha et al., 2010; Chen et al., 2013; Abete et al., 2014; Wang et al., 2016; Schwingshackl et al., 2017) can be countered by review papers that do not find this association (Han et al., 2019; Zeraatkar et al., 2019a; Zeraatkar et al., 2019b), and randomized controlled trials that do not find an association between reduced meat consumption and adverse health outcomes (Thomson et al., 2014). These citations are by no means an exhaustive list of the extensive nutrition literature, but are meant to be illustrative of an unsettled scientific field, and the fact that much nutritional epidemiologic research often posits implausible estimates of benefits or risks associated with diet (Ioannidis, 2018). The strongest evidence of a specific adverse effect is the increased risk of colorectal cancer with high intakes of processed meat. Conversely, various forms of micronutrient deficiencies affect some two billion people globally, particularly in developing countries. The greatest health burdens of this 'hidden hunger' are caused by deficiencies in zinc, vitamin A and iron, which lead to impaired growth, compromised immune functions and, in the case of iron, impaired cognitive development and reduced work capacity. An important factor contributing to these deficiencies is the consumption of mainly plant-based diets that are low in micronutrients, and in such situations, ASF can help reduce childhood stunting and malnutrition (Headey et al., 2018; Pimpin et al., 2019; Adesogan et al., 2020).

With regard to nutrition, a study of 137 plant-based meat substitutes (50 burgers, 10 ground, 29 sausages, 24 chicken, 9 seafood, 15 other) in Australia reported that the plant-based options were generally lower in kilojoules, total and saturated fat; but higher in carbohydrate, sugars, and dietary fiber as compared to meat. Less than a quarter of products were fortified with vitamin B12 (24%), iron (20%), and zinc (18%) (Curtain and Grafenauer, 2019). Consumers perceived that plant-based meat substitutes were healthier, but the wide variation in nutritional levels lends some support to the concern that consumers might run into nutritional deficiencies if assuming product equivalence when replacing ASF with plant-based products. Similarly, non-dairy milk beverages differ in their nutritional profiles (Clegg et al., 2021), and although most are fortified with calcium and vitamin D, the bioavailability of these substances after fortification has not been established (Singhal et al., 2017). In Spain, 54 soy beverages, 24 rice beverages, 22 almond beverages, 31 oat beverages, 6 coconut beverages, 12 miscellaneous beverages and 15 mixed beverages were analyzed, and the nutritional quality was found to be inferior to that of cow's milk and infant formula (Vitoria, 2017). There have been instances of nutritional disorders such as rickets in infants and toddlers fed predominantly or exclusively plant-based beverages (Le Louer et al., 2014; Vitoria, 2017). Baseline nutrition data for cell-based meat are not yet publicly available (Rubio et al., 2020).

An interesting summary of an Oxford-style debate outlining opposing views on the issue 'Children and adults should avoid consuming ASF to reduce the risk for chronic disease' was published in The American Journal of Clinical Nutrition (Barnard and Leroy, 2020). After framing this issue as a binary choice, the most common YES and NO arguments were outlined. One way forward, according to both sides, was to perform research studies comparing various formulations of omnivorous and vegan diets, while controlling for confounders as much as possible. It was agreed that such studies should involve participants at a variety of stages of life, and from a variety of demographic and cultural groups. Further, it was agreed that metrics beyond BW, lipids, and other cardiometabolic endpoints were needed to examine other health-related conditions, particularly cognitive, digestive, hormonal, and autoimmune diseases. However, as acknowledged in the article, 'such research may not resolve discordant worldviews, ethical frameworks, and philosophical investments that have marked this debate.' And that is really the challenge in discussions around meats and alternative meats. When different parties are coming at this issue with conflicting worldviews, no amount of data is going to reconcile these differences. So if science cannot help address ongoing points of disagreement, what are the underlying influences of these disparate world views, and are there any points of agreement?

Wizards, prophets and magicians

Garnett (2013) argues that three main framings can be applied to the challenge of how to reduce the environmental impact of feeding people better; namely a production challenge (wizard), a consumption or demand-side challenge (prophet), or a socioeconomic challenge, which I will term the magician. These terms in parenthesis reference Charles Mann's (2018) book 'The Wizard and the Prophet', which examines historical debates about agriculture and ecology through two distinct framings – pro-growth, pro-development, pro-technology wizards as exemplified by Norman Borlaug on one side; versus tradition-oriented, techno-skeptical, limits to growth-minded prophets as exemplified by William Vogt on the other. Briefly, the wizard is the sustainable intensification lens, the prophet envisions changing the dietary drivers of food production; and the magician, absent from Mann's book, sees more localized, diverse systems as better able to deliver the full range of micronutrients needed for good health – especially for women and children. This latter perspective tends to invoke a romanticized vision around smallholder production that can include some overly optimistic prophesying, hence the magician framing, and advocates for changes to the socioeconomic governance of the food system. None of these worldviews are necessarily mutually exclusive, and binary framings that pit them against each other tend to needlessly back proponents into artificially constructed corners. They each have their strengths and weaknesses; however, it is often difficult to productively engage people with alternative worldviews into considering how all three framings might be required to address future protein needs.

The promissory narrative associated with alternative meats is that this field provides 'kinder, healthier, fairer, tastier, safer and more sustainable approaches to conventional livestock products thus collectively work to make the ultimate promise of a better food system for all, and in turn a better food future for all' (Sexton et al., 2019). In some ways, it employs a wizard framing to solve the prophet's problem. This view tends to paint conventional livestock systems as outdated and primitive (Sexton et al., 2019). The response from some in the livestock industry has been to label alternative meats as 'artificial' and 'unnatural' in comparison with conventional ASF, due to the techno-scientific nature of their production. However, denigrating techno-scientific innovations in food production may backfire on the livestock sector by reinforcing the 'artisanal reaction'. This is a term used to describe the trend where consumers turn toward products that are apparently delivered by simpler and more natural processes in response to food scares alleged to be associated with overly industrialized production processes (Murdoch and Miele, 2004). If proponents of conventional meats demonize the use of GMOs in alternative meat production systems, they should not be surprised when consumers then fear the use of genetic engineering in agricultural production systems (Sexton et al., 2019). If cultured meats are framed as 'unnatural' to invoke unfounded health implications, then it is increasingly likely modern food production and processing methods will be feared, to the detriment of innovation in all production systems. Likewise, when alternative meat companies demonize animal agriculture by greatly overstating the impacts of livestock production based on widely debunked estimates in their marketing pitches [e.g. '51% of GHG emissions driven by livestock rearing and processing' whereas the number according to the FAO is 14.5% (Sexton et al., 2019)], they needlessly create antagonists. They should therefore not be surprised when the livestock sector, a potential ally in delivering on the mitigation efforts necessary to accomplish the shared goal of reduced GHG emissions and the primary caretakers of the land that will be 'released' from livestock production, become disenfranchised adversaries.

Sexton et al. (2019) noted that some alternative protein companies are suggesting they can actually provide both nutritional salvation and economic development for the hungry poor by providing low-cost, nutritionally rich and culturally tailored protein products in local Southern hemisphere contexts. These authors warn that alternative protein visions of feeding the world require critical reflection given the history of how productivist interpretations of global food security and single-sector economic development approaches have led to loss of livelihoods, increased inequality and land degradation for many pastoral communities in developing countries. They also note that advertising around alternative meats is designed to appeal to male carnivorous Western consumers who can continue to experience the taste and sensory pleasures of ASF by switching to alternative meats. The metaphoric link between meat and maleness in Western cultures has been noted by a number of scholars in the social sciences

(Sobal, 2005). Marketers use this to target those who subscribe to the metaphor and are therefore likely to be predisposed toward trying an alternative meat product (Rozin et al., 2012). It is perhaps no accident that a number of professional athletes have been employed to serve as spokesmen for alternative meat companies, alongside celebrity carnivore male chefs. This is reminiscent of the aforementioned 1960s advertising campaign to convince American men that consuming chicken was 'manly'. Ironically, this framing omits the very demographics – women and children in LMIC – who could most benefit from ASF and who have particular difficulty in obtaining adequate energy and essential micronutrients solely from bulky, plant-based diets (Dror and Allen, 2011).

There are other complex issues around conventional and alternative meat discussions that are often boiled down to an overly simplistic framing, or not even considered in the discussion. These include animal welfare, use of antibiotics, zoonotic disease, microbial contamination, food safety, biodiversity, ecosystem services, social justice, the slaughter of animals, the religious role of animals, the cultural appropriateness of food, patents, food sovereignty, and food choice. The current dichotomous framing of plant versus animal; synthetic versus natural; extensive versus intensive; clean versus dirty; GMO versus organic; alternative versus real; tradition versus progress is not helpful for discussions relating to food systems. These discussions are not unidimensional. And the framing will ultimately impact which stakeholders are willing to participate in proposed solutions. It is possible to simultaneously work to improve the efficiency of animal source foods, plant source foods, and cultured meat production systems without denigrating any of them. There is value in seeking to move beyond 'us versus them' framings, focusing on shared values around sustainable meat futures (Sexton et al., 2019).

Moving forward

The FAO (FAO, 2019) outlines five practical actions that can be widely implemented for measurable and rapid impacts on livestock emissions. These include (1) boosting efficiency of livestock production and resource use; (2) intensifying recycling efforts and minimizing losses for a circular bioeconomy; (3) capitalizing on nature-based solutions to ramp up carbon offsets; (4) striving for healthy, sustainable diets and accounting for protein alternatives; and (5) developing policy measures to drive change.

Boosting efficiency sounds very much like the production challenge framing. This could include technological innovations in feeding, breeding, genetics, animal health, management, and information technology to reduce environmental impacts relative to the amount of livestock product. It is this approach that has already dramatically reduced the emission intensity of ASF in MHIC, especially in so-called 'high-input' or intensive systems in which external inputs such as supplementary feeds, veterinary medicines and advanced breeding and reproductive technologies are relatively easily obtainable and widely used. This is reflected in the global yield per animal maps for beef (Fig. 5) and milk (Fig. 6).

Cattle, as large ruminants, hold an iconic position in many climate and sustainability discussions. The FAO estimated cattle numbers at 1.511 billion head in 2019 (FAOSTAT, 2020) and Fig. 7 shows global cattle numbers versus beef production for some of the major cattle producing countries and regions of the world. The United States is the largest single beef-producing country followed by Brazil. These two countries, along with Europe, collectively produced approximately 50% of the world's beef in 2020. However, this number does not reflect the distribution of global cattle populations. Brazil is the country with the largest number of cattle at 215 million head, with India coming in second at 193 million head. It should be noted that these figures are only for cattle. It does not include the world buffalo stocks of 204 million animals, of which 110 million head live in India. Likewise, Pakistan has almost the same number of buffalo (40 million) as cattle (48 million) totaling 88 million head. Likewise, beef production numbers are usually referring to cattle. If buffalo meat and edible offal from both are included in the production numbers, the values for India and Pakistan more than double from 0.9 and 1.1, to 2.9 and 2.4 MMt, respectively.

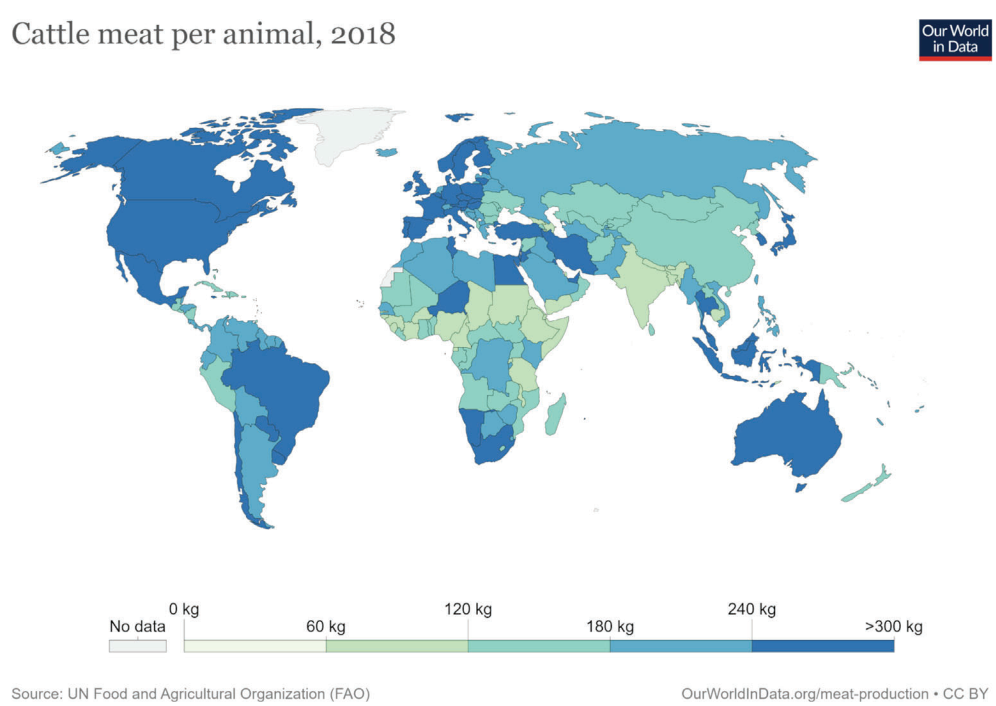

Fig. 5. 2018 global beef productivity (kg of beef per animal). Reproduced from Ritchie and Roser (2019) with data from FAO (2020).

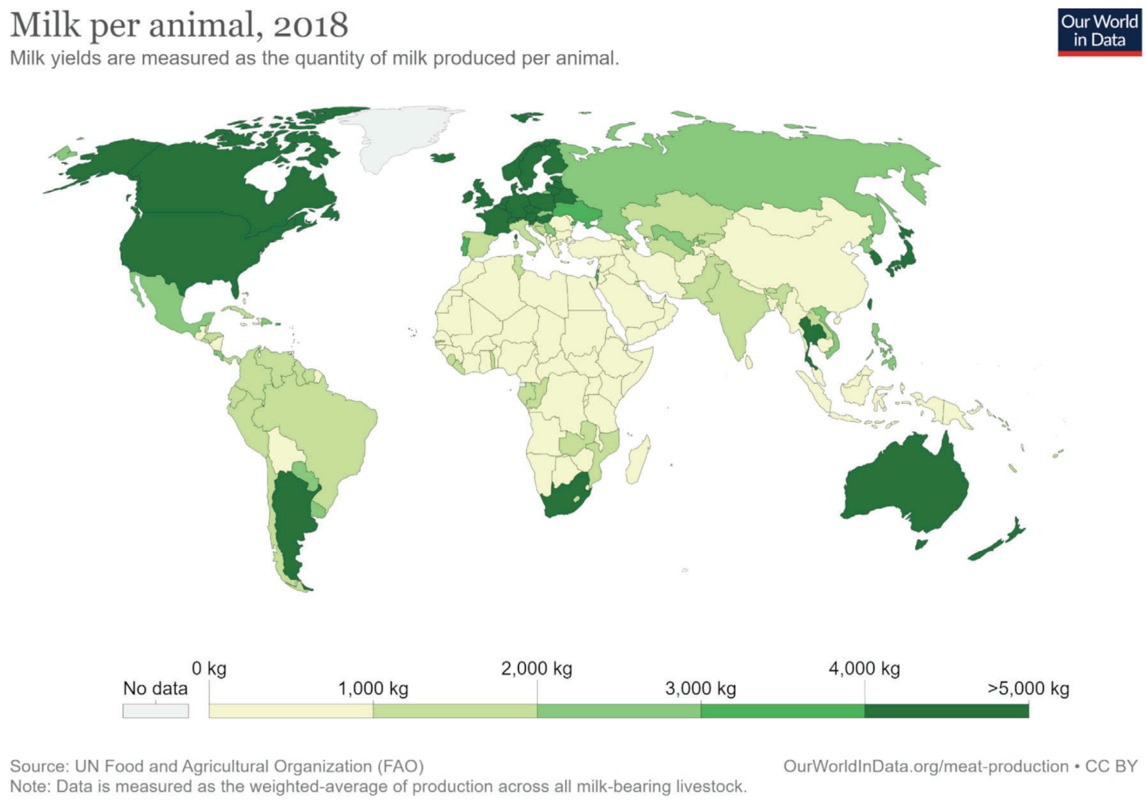

Fig. 6. 2018 global milk productivity (kg of milk yield per animal). Reproduced from Ritchie and Roser (2019) with data from FAO (2020).

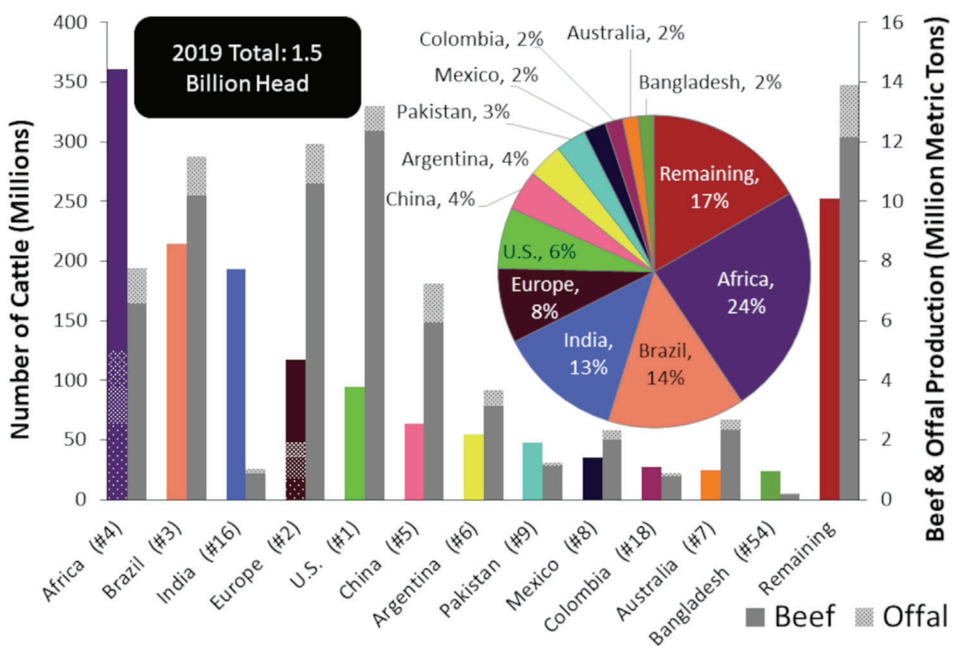

Fig. 7. Comparison of percentage of cattle population (pie chart), cattle numbers and beef/offal production for countries and regions of the world. World beef production rank is listed next to country/region name. The cattle number bars representing regions (i.e., Africa and Europe) are ordered by the top 3 countries (patterns) and then the remaining countries of a region (solid). Data are from FAO (2020).

Africa collectively is home to 361 million cattle, 24% of the global population, and 3.5 million buffalo located mainly in Egypt. In Africa, the agricultural sector is the largest sector of the domestic economy, and livestock are a crucial component of that sector and account for more than 70% of African agricultural GHG emissions. Ethiopia has 63 million cattle, the most of any African country, followed by Sudan and Chad each at 31 million head, Tanzania with 28 million head, Kenya and Nigeria each with 21 million head, Uganda with 16 million head, and Niger, South Sudan, South Africa, Mali and Burkina Faso each with 10–15 million head. Over 250 mil-

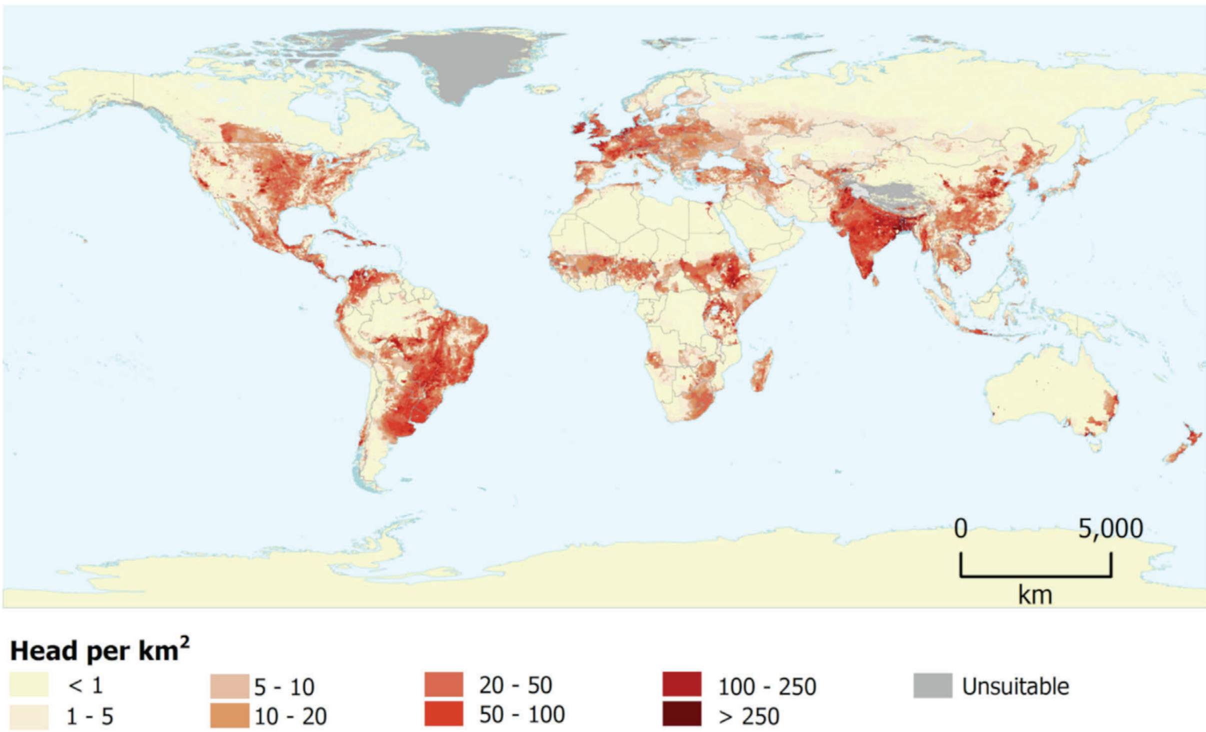

Fig. 8. Global distribution of cattle. Reproduced from Robinson et al. (2014).

lion cattle live outside of the top beef producing countries and the African continent, reflecting the fact that cattle are found throughout the world, in almost all climatic zones, with the exception of high elevations. They live in more than 200 countries around the world, and they have been bred for adaptations to heat, cold, humidity, extreme diet, water scarcity, mountainous terrain, dry environments, and for general hardiness. Cattle also produce milk, and in 2019, the world production of fresh cow milk was almost 715 MMt, of which 90 MMt was produced in India, and 36 MMt was produced in Africa. As with meat, a lot of milk is also produced by buffalo in India, 92 MMt according to the FAO, making India the largest dairy country, producing an estimated 21% (188 MMt) of the world's 883 MMt of milk from all species in 2019. The highest cattle densities are found in India, the East African highlands (particularly in Ethiopia), Northern Europe and in South America (Fig. 8).

Only 7% of beef (2% cattle population) is produced in intensive systems. Likewise, approximately 88% of milk production occurs

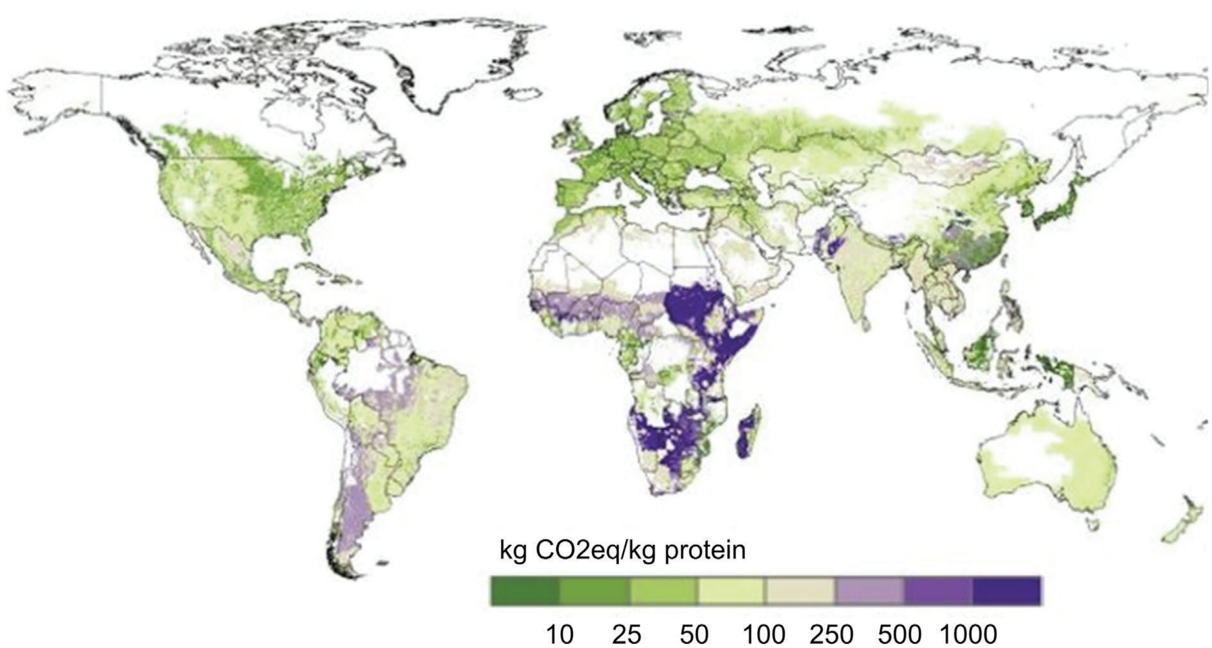

Fig. 9. Global greenhouse gas emissions from beef production in 2010 expressed as kg of CO_2 equivalents per kilogram of protein. Reproduced from Herrero et al. (2013).

within mixed crop and livestock systems, with only 12% being produced in intensive systems (Gerber et al., 2015). The majority of beef, 59% (63% cattle population), is produced in mixed crop and livestock systems, with the remaining 34% of total beef (35% cattle population) being produced on grazing systems. This later group can be further divided into intensive grazing systems that are found in tropical and temperate zones where high-quality grasslands and fodder production can support larger numbers of highly productive animals. These systems are mostly focused on food production, based on individual landownership, and supply about 20% of global beef production. The second category represents pastoral livestock systems that have developed in harsh environments, such as dry lands and cold areas, and which account for less than 15% of total beef production, but which support the livelihoods of 200 million households. These are driven by low animal productivity across large areas of arid lands, feed scarcity, and animals with low productive potential that are often used by smallholder farmers for other services such as draft power, manure and to manage household risk. It should be noted emissions attributable to animals used for draft power are typically excluded from the calculation of meat and milk emission estimates for that species (Gerber et al., 2013). These authors note the efficiency improvements based solely on saleable ASF products that result in herd size reductions could harm traditional farm household livelihoods due to the loss of the non-food goods and services provided by livestock.

The developing world currently contributes 75% of global GHG emissions from ruminants and 56% of emissions from monogastrics (Herrero et al., 2013). There is a wide gap in emission intensities that exist on a global and regional scale (Fig. 9), and considerable variation between producers. It has been found that the environmental impact of producing the same product can vary by 50-fold (Poore and Nemecek, 2018). It is estimated that the potential for mitigating livestock emissions – CH_4 in particular – by applying the practices of the top 10th percentile of producers with the lowest emission intensities in a given system, region and agro-ecological zone is between 30 and 35% (FAO, 2018). Chang et al. (2021) reported that 88–91% of the livestock CH_4 emissions come from enteric fermentation by ruminants (i.e. cattle, sheep, goats, and buffaloes). They predicted that if there are no improvements in CH_4 emissions per kg protein, then global livestock CH_4 emissions will increase by 51–54% from 2012 to 2050. They estimated that improving production efficiencies in 10 countries (Brazil, China, India, Iran, Madagascar, Morocco, Niger, South Africa, Tanzania, Turkey) where a large increase in livestock production is projected and the current CH_4 emissions per kg protein are high could contribute 60–65% of the global reduction in livestock emissions by 2050 (compared to a baseline where emission intensities are held constant in the future). They further found that efforts to improve production efficiency have a much greater potential for GHG mitigating effects than would demand-side efforts to promote balanced, healthy, and environmentally sustainable diets.

In this increased efficiency strategic perspective, the livestock sector (and its sectoral organizations) is identified as an important stakeholder in delivering on the mitigation efforts necessary to reduce GHG emissions and to improve its environmental footprint (Gerber et al., 2013). However, the efficiency improvements need to be undertaken with careful consideration of livelihood concerns. Cattle produce meat, milk, fibers, hides, skins, fertilizer and fuel, and are used for transportation and draft power. They also serve socioeconomic, cultural and ecological roles other than food and income, such as asset building in the form of stock accumulation, particularly in Africa and parts of Asia, and religious worship in India. Any proposed strategies for boosting the efficiency of cattle production need to consider these broader concerns, and also the fact that access to technologies may more be limited in some settings, often because of factors such as inaccessibility, unaffordability, lack of relevant knowledge, and/or of organizational capacity. This boosting efficiency framing could equally include the need for improved efficiencies of systems for producing alternative meats to bring these products to market at scale and cost parity, and with a comparable nutritional profile to conventional ASF, which could include innovations in facility design, optimized culture media for cell growth, cell line selection and differentiation, synthetic biology, and microbial contamination control strategies (Post et al., 2020).

Globally, approximately 86% of the feed DM ingested by livestock is inedible by humans (Mottet et al., 2017), and likely an even high proportion in several developing countries where ruminant livestock subsist mainly on pastures and crop residues (Adesogan et al., 2020). Crop production, processing and the agrifood chains produce large amounts of residues as well as co- and by-products, which constitute nearly 30% of global livestock feed intake. These products will be produced in ever increasing amounts as the human population grows and consumes more processed food. Livestock play, and will continue to play, a critical role in adding value to these residual products, a large share of which could otherwise be an environmental burden. Intensifying recycling efforts and minimizing losses for a circular bioeconomy include measures such as recycling clean sources of food waste as livestock feed, and adopting innovations in resource re-use. Unused crop residues, food waste, and agro-industrial by-products are lost opportunities to recycle and optimize resource use efficiency and can be repurposed for animal feed. Additionally, manure and slaughterhouse waste can be used to generate fertilizer and biogas as a source of renewable energy. Similarly recycling of spent culture media, and water from bioreactor cleaning will be an important requirement for scaling up of cultured meats. Ironically livestock are already an important source of food processing waste, and perhaps livestock, particularly monogastrics, could potentially play a role in recycling spent culture media.

The GHG mitigation potential of the livestock sector could represent up to 50% of the global mitigation potential of the agriculture, forestry and land-use sector; however, the share that could be achieved at a reasonable economic cost is likely smaller (Herrero et al., 2016). The livestock sector is uniquely positioned to help mitigate its own emissions if accounting of net carbon sequestration is included in LCAs. For measures targeting soil carbon sequestration in grazing lands, mitigation potentials for animal GHG emissions at unit costs of US$20, US$50 and US$100 per t CO_2 were estimated at 250, 375 and 750 MMt CO_2eq annually (Metz et al., 2007). Emissions pricing could push up global food prices and reduce consumption in low-income regions, with negative impacts on food security (Herrero et al., 2016). It may be that well-managed grazing on degraded rangelands can help to capture soil organic carbon. Additionally, silvo-pastoralism offers further potential benefits (Buckley Biggs and Huntsinger, 2021; Sales-Baptista and Ferraz-de-Oliveira, 2021). There is also an opportunity to use manure and other waste from livestock farms to generate biogas, and to place solar panels in a way that not only captures sunlight for energy but also provides shade for livestock (Maia et al., 2020; Sharpe et al., 2021). Other opportunities include use of feed additives, improved feed digestibility, improved manure and animal management, and better feeds (Caro et al., 2016). For example, it could be envisioned that green renewable natural gas produced from biomethane captured from California's dairy industry could be used to provide a decarbonized source of power for colocalized alternative meat manufacturing facilities.

Striving for healthy, nutritious diets for all requires a simultaneous understanding that while consumers in MHIC would benefit from reduced consumption of calories and ASF, consumers in LMIC would benefit from improved access to ASF. While changes in diets

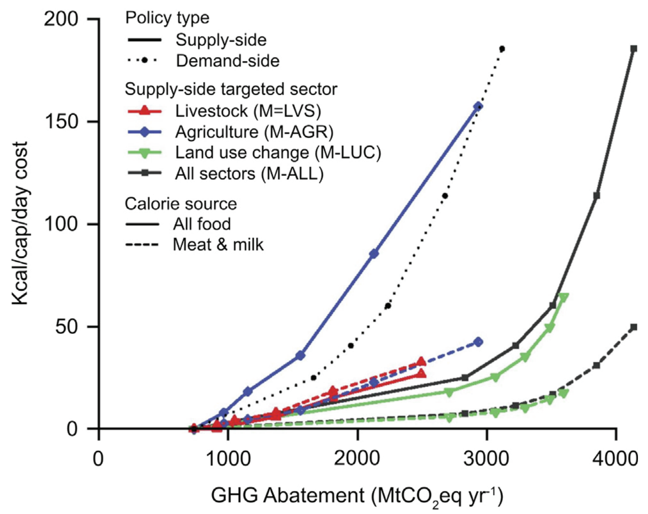

Fig. 10. Total abatement calorie cost curves for mitigation policies targeting different sectors on the supply-side through carbon price or targeting the demand-side through consumption reduction. Plain thick lines indicate the loss of total food calories and dashed thick lines the loss of animal calories only. Greenhouse gas (GHG) abatement is calculated as the difference between emissions under scenario DYN (2030 dynamic livestock sector capable of responding to economic drivers by adapting the structure of production systems to the changing environment) with a climate policy and emissions from the reference scenario FIX (counterfactual scenario in which the relative distribution of ruminants across the different livestock production systems was kept as it was in 2000, without climate policy). Data points correspond to carbon prices of US$0, US$5, US$10, US$20, US$50, and US$100 per tCO_2eq. The demand-side curve (thin dotted line) represents the abatement resulting from restricting consumption to levels calculated under the ALL mitigation policy, M−ALL, but without a carbon price. Reproduced from Havlík et al. (2014).

might be a GHG mitigation option in developed countries, GHG mitigation policies designed to reduce ASF demand were found to be less effective than supply-side policies, and to come at a higher calorie cost (i.e. less food available) which could lead to further malnutrition or undernutrition in the developing world (Havlík et al., 2014). These authors also found that GHG mitigation policies targeted to prevent land-use change were 5–10 times more efficient than policies targeting direct livestock emissions. The emission reductions achieved under a demand-side policy were, depending on the level of calorie availability decrease, 30–80% less effective in reducing emissions than its supply-side policy equivalent (Fig. 10). This means that the demand-side policies modeled in that study resulted in substantially higher calorie reductions to achieve the same GHG mitigation levels as the supply-side policies were able to achieve by directly targeting emissions from agriculture and land-use change. There is also potential for innovations in biotechnology to produce alternative meats with an improved nutritional profile, and improved feedstuffs for both cultured animal cells and livestock. This might include algal, fungal, insect or microbial protein, or synthetic aminoacids being added to livestock feed, or cell culture media. There are also some promising feed additives that work to reduce CH_4 emissions (Roque et al., 2019). Consumer acceptance of these innovations is going to be critical (Bryant and Barnett, 2018).

Policy measures to drive change are perhaps the area where it might be most difficult to find agreement among varying stakeholders. Options span market-based instruments (e.g. carbon pricing, meat taxes, incentives etc.), investments in infrastructure and support for research and development in both conventional and alternative meats, and direct regulatory interventions. Some policies, such as incentivizing farmers to adopt better practices to reduce emissions without lowering production (e.g. mitigation subsidies), are likely to be easier to implement than negative incentives such as a carbon tax, or demand-side interventions (e.g. taxing meat (Springmann et al., 2018)) to cause a shift to low-emissions food. Modeling carbon taxation against ruminant production systems at US$52/t CO_2eq in the UK and France was found to result in socioeconomic losses that far outweighed the value of the environmental benefits (Lee et al., 2021). Win-win outcomes that reduce emissions such as recycling by-products, producing biogas from methane, or capturing soil organic carbon through restoring degraded grasslands with well-managed grazing systems are likely to be more popular than those that result in forced reallocation of resources and large macroeconomic welfare losses, or diminished food security. It is likely that various stakeholders will weigh these trade-offs differently, but top-down interventions that ignore or dismiss these trade-offs are likely to encounter fierce stakeholder opposition. People generally do not like to be told what to think, how to act, or what to eat.

Sustainability discussions bring in multiple competing goals, and often-conflicting outcomes emerge depending how antagonistic goals are balanced. The most environmentally friendly diet might be the least healthy option, or the least palatable, or nutritionally inadequate, or the most expensive, or culturally unacceptable. The trade-offs among production, environmental protection, food and nutrition security, food affordability, livelihoods, human and animal health and welfare are all part of sustainability discussions, and they must be explicitly included in discussions around policy options.

Communicating complexity

The public debate surrounding the global livestock sector is becoming increasingly polarized, with advocates of reductions in meat consumption being challenged by counter narratives that seek to defend ASF, the livestock industry and the rural livelihoods associated with it (Maye et al., 2021). There is very diverse literature related to the likely impact of alternative meats on a number of different metrics written by subject matter experts in very disparate fields, ranging from technical production aspects, nutritional and human health impacts, behavioral economics and behavior change, policy implications, and environmental and sustainability ramifications. As with all disciplines, there is a minority of experts among a majority population of non-experts. It can be difficult for those with expertise in livestock production systems to make themselves heard. In the words of Salmon et al. (2020), '*The application of scientific information outside the science community is to some extent uncontrollable; nevertheless, the livestock community must remain broadly objective and balanced in presenting information about global livestock production and both its future role in sustainable diets and impacts on broader sustainable development goals.*'

The livestock sector has complex interactions with more than half of the UN sustainable development goals (FAO, 2018). Numerous narratives in favor of alternative proteins have emphasized the ability for these novel foods to 'disrupt', and thus overcome the negative impacts associated with conventional livestock production. Aspirational rhetoric calling for an end to animals in the global food system by 2035 might play well with Silicon Valley venture capitalists (Stephens et al., 2018), but it is breathtakingly naïve given the importance of animals in global food systems. Much of the discussion around alternative meats is taking place in high-income countries (Fig. 1), where malnutrition takes the form of excessive food intake resulting in obesity and associated non-communicable diseases. In LMIC, malnutrition takes the form of undernourishment and micronutrient deficiencies. Companies pledging to eliminate livestock apparently overlook the hundreds of millions of pastoralists in South Asia and sub-Saharan Africa, two-thirds of whom are women, and many of whom depend on livestock for food and livelihoods (Niamir-Fuller and Huber-Sannwald, 2020). Steve Myrick, Vice President of operations at Silicon Valley-based Memphis Meats, recently renamed Upside Foods, stated that his company wants to 'augment, not disrupt' the mix of food production methods in the next five to 10 years. He continued, 'we have this philosophy of a big tent. We want to partner with existing industry, coexist, respect consumer traditions', demonstrating a promising move away from the unhelpful binary 'us versus them' framing.

Productive interactions among relevant subject matter experts explicitly identifying the multitude of socio-economic and environmental considerations and trade-offs associated with proposed changes in a complex system such as the livestock sector, and as compared to alternative meat options, will be essential given the complexity of sustainable diets (Tuomisto, 2019a). The global food system is far too diverse and driven by unique environmental and socioeconomic circumstances to allow for a one-size-fits-all policy recommendation (van Vliet et al., 2020). Undoubtedly addressing future food demands will require efforts and investments to increase the environmental efficiency of all food production systems. However, this approach on its own will not deliver a sustainable food system. We need a diversity of voices including wizards, prophets and magicians, farmers, men and women to be involved in developing nutritionally and culturally appropriate food production systems using plants, animals, and cellular agriculture to sustainably address future demand. Proposing major changes in agricultural systems such as replacing ASF requires interdisciplinary and multi-sectorial collaborations, and a nuanced understanding of the impacts of such changes on the multiple interconnected pillars of sustainability (Lee et al., 2021). Furthermore, it is important that the ability to employ innovative technologies in food production systems be preserved. Spreading misinformation or fear around food innovations jeopardizes access to these tools for all food-producing sectors, reducing future opportunities for the co-delivery of nutritious food with a reduced environmental impact.

Ethics approval

Not applicable.

Data and model availability statement

None of the data were deposited in an official repository.

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Author contributions

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Declaration of interest

None.

Acknowledgements

We acknowledge Maci Mueller for the preparation of Fig. 7.

Financial Support Statement

This research received no specific grant from any funding agency, commercial or not-for-profit section.

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