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Meat Consumption and Sustainability

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Abstract

Meat has become a controversial topic in public debates, as it involves multiple sustainability dimensions. Here, we review global meat consumption trends and the various sustainability dimensions involved, including economic, social, environmental, health, and animal welfare issues. Meat has much larger environmental and climate footprints than plant-based foods and can also be associated with negative health effects. Technological options can help to increase the sustainability of meat production, but changes in consumption are required as well. At least in high-income countries, where people consume a lot of meat on average, notable reductions will be important. However, vegetarian lifestyles for all would not necessarily be the best option. Especially in low-income countries, nutritious plant-based foods are not available or affordable year-round. Also, livestock production is an important source of income for many poor households. More research is needed on how to promote technological and behavioral changes while managing sustainability trade-offs.

1. INTRODUCTION

Meat consumption is one of the most discussed topics in the broader public debates about sustainable food systems, climate change, and healthy nutrition (Sanford et al. 2021, Willett et al. 2019). The public focus on meat is unsurprising, as meat production and consumption relate to several key sustainability dimensions. On the one hand, meat can promote sustainable development, as the meat production sector is a source of income and employment for over one billion people worldwide, many of them in developing countries (Salmon et al. 2020). Meat is also a rich source of nutrients required for human nutrition—such as proteins, vitamins, and minerals—so that meat consumption can help reduce nutritional deficiencies and thus promote human health (Headey et al. 2018, Zaharia et al. 2021). Finally, the meat production sector can convert grass and crop residues that are inedible for humans into human food, hence contributing to food security on a planet with finite natural resources (Mottet et al. 2017).

On the other hand, meat has much larger environmental and climate footprints than plant-based foods (Poore & Nemecek 2018). For instance, the livestock sector is a core driver of biodiversity loss in some regions and accounts for a large share of agriculture's greenhouse gas (GHG) emissions (Henry et al. 2019, Xu et al. 2021). In some husbandry systems, meat production is also associated with severe animal welfare issues (Grethe 2017). Finally, meat production and consumption can be associated with human health issues, likely increasing the risk of air quality–related health harms, certain chronic diseases, and zoonoses (Domingo et al. 2021, Gilbert et al. 2021, Yang et al. 2016). These negative effects of meat on sustainable development are also the main reason why a rising number of people are turning vegetarian or flexitarian, meaning that they try to reduce meat consumption as much as possible. Alternatives to classical meat, such as plant-based meat and lab-grown meat, are currently hyped as more sustainable options, yet some of their potential effects on nutrition, health, and the environment still warrant further scrutiny (Dolgin 2020, Rubio et al. 2020).

In this article, we review global meat consumption trends and the various sustainability dimensions involved, including economic, social, environmental, health, and animal welfare issues. The term meat here refers to the flesh of warm-blooded animals used for food, including mammals and birds but excluding fish and insects. We also pursue the question whether reduced meat consumption could promote sustainable development, concluding that, at least in high-income countries, notable reductions would be desirable and important. However, nuance is required. Vegetarian lifestyles for all would not necessarily be the best option due to trade-offs in the different sustainability dimensions. Our analysis adds to the literature, as most existing reviews have focused on selected aspects of meat production and consumption, such as health aspects, environmental aspects, or the food-feed competition, yet neglecting other important aspects (Adesogan et al. 2020, Gilbert et al. 2021, Godfray et al. 2018, Mottet et al. 2017). A broad focus on all relevant sustainability dimensions is important to better understand possible synergies and trade-offs, which is needed for guiding more sustainable meat futures.

2. GLOBAL TRENDS IN MEAT CONSUMPTION

Over the last several decades, global meat consumption has increased tremendously. Notable increases in total consumption have been observed in all world regions, but especially in Asia, Latin America, and Africa (**Figure 1*a***). In terms of meat types, pork and poultry dominate in today's global consumption and have seen the strongest consumption increases (**Figure 1*b***). The increase in pork consumption is primarily driven by China and a few other countries in Southeast Asia. In contrast, poultry consumption has sharply increased in all parts of the world, as it is cheaper, often perceived as healthier, and less affected by religious restrictions than other meat types (Mottet &

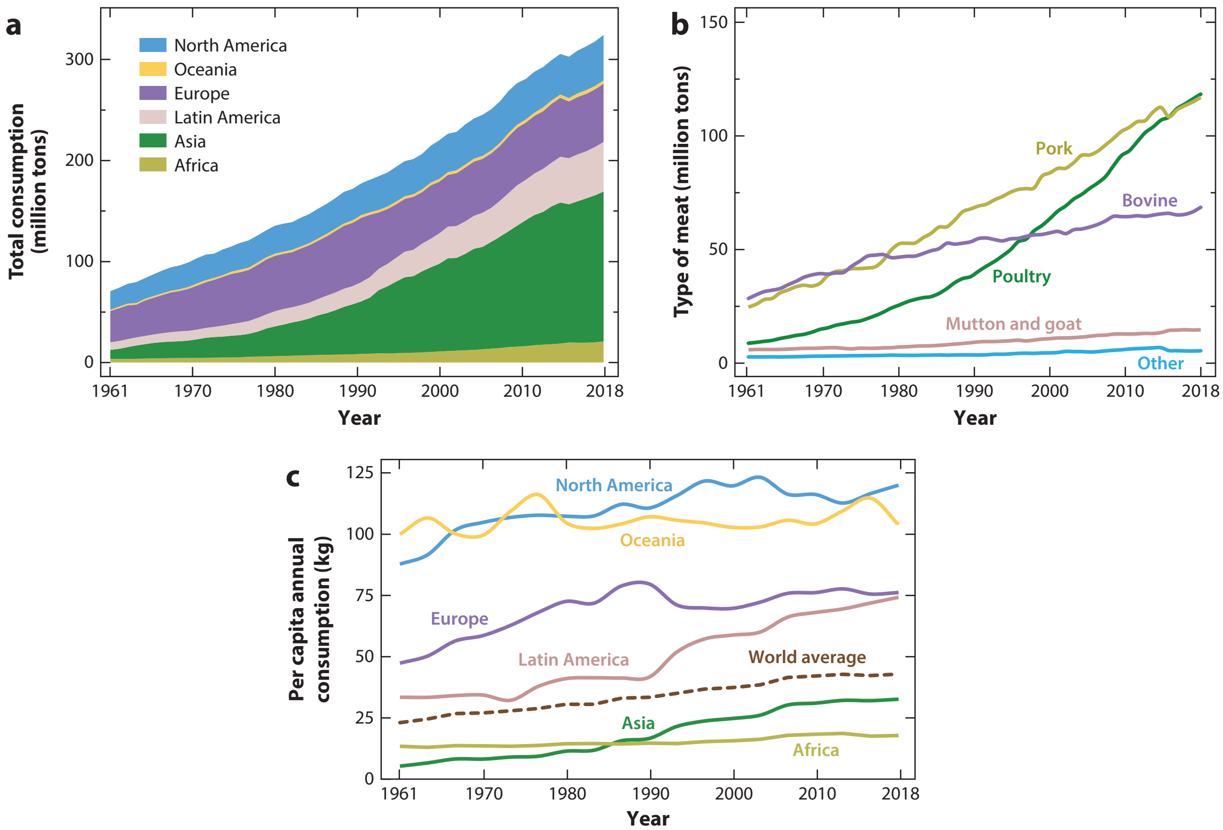

Figure 1

Global meat consumption. (*a*) Total annual consumption by region, (*b*) total annual consumption by type of meat, and (*c*) per capita annual consumption by region. Data from FAO Food Balance Sheets (**https://www.fao.org/faostat/en/#data/FBS**).

Tempio 2017). Although to a lesser extent, the global consumption of bovine meat, mutton and goat, and other meat types has also increased over time.

One main driver of global meat consumption trends is population growth. Another key driver is income growth, contributing to higher levels of meat consumption per capita. As expected, average consumption levels per capita are highest in the rich countries of North America, Oceania, and Europe, even though in these regions, consumption levels have hardly increased since the 1990s (**Figure 1***c*). Starting from much lower levels, stronger increases have recently been observed in low- and middle-income countries of Africa, Asia, and Latin America. Especially in Latin America, average per capita consumption levels are gradually catching up with those in rich country regions.

The relationship between income and per capita meat consumption is complex and analyzed in more detail in **Figure 2**. In most low- and middle-income countries, rising gross domestic product (GDP) is associated with rising per capita meat consumption, whereas in many rich countries, consumption levels are stagnating or even declining with further rising GDP. This stagnation in rich countries can likely be explained by demographic and preference shifts, including rising consumer concerns about animal welfare and the environment, even though the concrete role of different factors is not yet well explored and may differ by country and cultural context.

Generally speaking, the patterns observed in **Figure 2** resemble those of an environmental Kuznets curve, with a positive income-meat consumption relationship at low- and middle-income

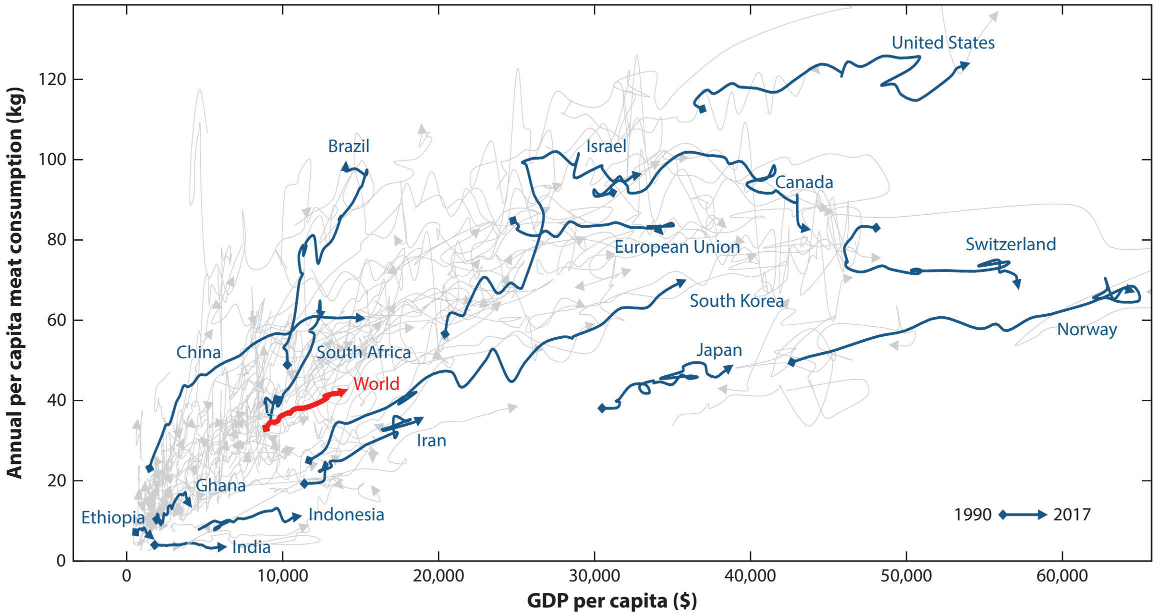

Figure 2

Development of per capita meat consumption and gross domestic product (GDP) over time (1990–2017). Each arrow reflects the development of per capita meat consumption and per capita GDP (in constant international dollars) for a particular country. Selected countries are highlighted with blue arrows. All other countries with populations above one million people are shown with light grey arrows in the background. Data from the World Development Indicators (**https://databank.worldbank.org/source/world-development-indicators**) and FAO Food Balance Sheets (**https://www.fao.org/faostat/en/#data/FBS**).

levels and then a stagnation or decline beyond the point of "peak meat" (Spiller & Nitzko 2015, Vranken et al. 2014). Global data suggest that peak meat occurs at per capita incomes of approximately 36,000 international dollars (Cole & McCoskey 2013). Currently, most of the world population lives in countries well below this income level; 75% even live in countries with mean per capita incomes less than 18,000 international dollars.

Simply based on income and demographic projections, global meat demand would continue to rise until 2050, mostly driven by low- and middle-income countries (Desiere et al. 2018, Gouel & Guimbard 2019). In the second half of the twenty-first century, global meat demand might start to fall, although the long-term trends remain uncertain (Bodirsky et al. 2015, Valin et al. 2014). However, beyond income and population trends, there may be resource and environmental constraints that could limit further growth in global meat supply and demand. Hence, how exactly the future of meat consumption may look in the medium and long run is difficult to predict. Related aspects and possible meat futures are discussed in subsequent sections.

3. ECONOMIC AND SOCIAL ASPECTS

Meat and livestock are important subsectors of the overall food system with manifold economic and social effects along relevant value chains, including meat production, processing, packaging, transport, and retail. Globally, livestock accounts for about 40% of the total agricultural production value; livestock value chains are estimated to employ more than 1.3 billion people (Salmon et al. 2020).

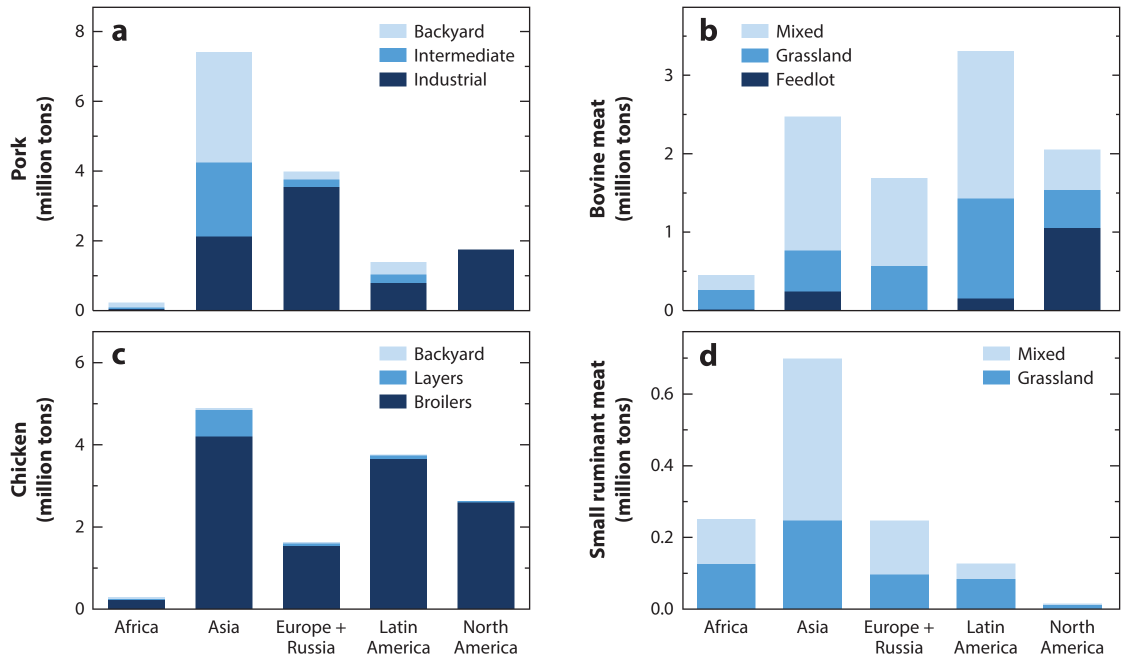

Figure 3

Meat production by region and production intensity in millions of tons. Production volumes measured in terms of protein. Data from the Global Livestock Environmental Assessment Model (FAO 2021a).

3.1. Meat Production Systems

Meat production systems can differ remarkably, depending on local resource endowments, available technologies, and cultural norms in a particular context. Important criteria of differentiation include the type of meat produced, intensity of production, relation to land, and degree of integration with crop production activities (Steinfeld et al. 2006). **Figure 3** shows the role of different meat production systems by geographic region and type of meat produced. Intensive and industrial systems characterized by high levels of technology and capital intensity dominate global meat production, especially for pork and poultry (Gilbert et al. 2015). Backyard systems, which are primarily intended for subsistence and local market sales and where feed is largely derived from crop residues and by-products, used to play a larger role in the past but only account for relatively small production shares today. One exception is pork in China and other parts of Asia, where backyard systems still make up a sizeable share of total production (Gilbert et al. 2015, Mottet et al. 2017). In Africa, backyard systems are also important for pork and chicken, even though total production quantities are small (**Figure 3**). Cattle and small ruminants are often integrated into mixed crop-livestock production systems, where they convert crop products and residues into nutrient-dense foods and manure (Mottet et al. 2017).

3.2. Competition Between Food and Feed

A relevant issue in the sustainability discourse around meat and global food security is to what extent livestock feeds on resources that can be used as food by humans directly. Recent estimates suggest that only around 15% of all dry matter used as livestock feed is in direct competition with human food; the other 85% mainly consists of grass and leaves, crop residues, and inedible by-products (Mottet et al. 2017). However, these numbers need some further reflection in order to avoid misinterpretation. First, even though they account for only a relatively small share of the total dry matter, feed crops are cultivated on 560 million hectares (40% of the total cropland worldwide) where they compete with food production for direct human consumption. Second, of the two billion hectares of grassland used for livestock feed, about one-third could potentially be converted and used as cropland. Important to note is that almost all of the unconvertable grassland is located in low- and middle-income countries and mainly used to graze small ruminants (Mottet et al. 2017).

Livestock species differ considerably in terms of their feed sources and energy/protein conversion rates. Ruminants generally require more land and larger feed quantities per kilogram of meat than monogastric animals (e.g., pigs, poultry). Nonetheless, ruminants are able to digest roughage and can thus utilize low-opportunity-cost land and feed, which do not compete with human food, to produce highly nutritious protein (van Zanten et al. 2016). Monogastric animals can only digest simple carbohydrates, so their feed is more often in direct competition with human food. Hence, simple comparisons of feed or land requirements per unit of output between livestock types can be confusing. Livestock production on marginal lands unsuitable for crop production can be a resource-efficient way of food production. At the same time, reducing the production of feed on cropland could result in substantial efficiency gains in terms of food production per unit of land (Schader et al. 2015).

3.3. Social Aspects of Livestock Production

As mentioned, the livestock sector is an important source of income and employment for many households. In low- and middle-income countries in particular, livestock also provide draught power and transportation, bring prestige to individuals and communities, help to store wealth, and function as insurance (Baltenweck et al. 2020, Herrero et al. 2013). Moreover, livestock can affect social inclusiveness and equity. Backyard and small-scale production systems are important activities of poor households with limited economic opportunities (Salmon et al. 2020). For women in developing countries, livestock are sometimes among the few productive assets they are allowed to own. Hence, livestock ownership can represent a pathway toward female empowerment (Baltenweck et al. 2020, Salmon et al. 2018), with potential positive implications for child nutrition (Jin & Iannotti 2014). Some of these social functions of livestock are not always fully considered in the global sustainability discourse, even though they can be of great importance for the well-being of large population groups (Adesogan et al. 2020).

However, small-scale livestock production can also reinforce social inequalities through specific mechanisms. The risk of zoonotic diseases is often highest for the poorest livestock holders due to their close contact with the animals and their limited access to healthcare services (Grace et al. 2017). Child labor is common for herding livestock in many rural and pastoralist communities, with negative consequences for child education and future income opportunities (Webbink et al. 2012). These negative effects deserve attention, even though they are unlikely to outweigh the more numerous socioeconomic benefits of livestock for the poor.

Industrial meat production systems have fewer positive effects on social equity in general. While large-scale units create farm and off-farm employment (Sneeringer & Hertz 2013), working conditions are often poor, especially in the meatpacking industry (Ramos et al. 2021). Industrial meat production facilities can also contribute to social injustice, due to environmental pollution and falling property values in the immediate neighborhoods, which are often primarily inhabited by socially disadvantaged groups (Chamanara et al. 2021, Lawley 2021). Analyses of the social effects of industrial meat production so far concentrate mostly on high-income and, to a lesser extent, middle-income countries.

4. ENVIRONMENTAL ASPECTS

The production of meat has significantly larger environmental and climate footprints than the production of plant-based foods (Godfray et al. 2018). Accounting for less than 20% of the global food energy, meat and dairy use 70% of all agricultural land and 40% of the arable cropland (Mottet et al. 2017, Poore & Nemecek 2018). Animal-sourced foods are responsible for more than one-quarter of humanity's freshwater footprint (Gerbens-Leenes et al. 2013) and up to two-thirds of all food-related GHG emissions (Poore & Nemecek 2018, Springmann et al. 2018a, Xu et al. 2021). About 20% of global nitrogen and phosphorus applications are attributable to animal-sourced foods, contributing to the pollution of terrestrial and aquatic ecosystems (Springmann et al. 2018a). Meat production is also considered one of the core drivers of global deforestation and biodiversity loss (Henry et al. 2019, Machovina et al. 2015). Hence, further increasing meat production and consumption according to the trends described in Section 2 would likely lead to the collapse of some global ecosystem functions on which humanity crucially depends (Springmann et al. 2018a).

Beyond global environmental issues, meat production is associated with numerous externalities at local levels. Extensive grazing systems can contribute to positive externalities in terms of grassland biodiversity and multifunctional landscapes (Yuan et al. 2016), but in intensive systems the negative externalities dominate. In particular, feedlots are associated with poor water and air quality, including elevated levels of particulate matter, with negative health consequences for local communities (Chamanara et al. 2021). In the United States, for example, red meat production is a major factor behind air quality–related health harms: A recent study showed that per serving, red meat is associated with 15 times more air quality–related harms than plant-based foods on average (Domingo et al. 2021).

Given the important role of livestock for some of the key global environmental goods, three aspects are discussed in more detail in the following subsections, namely water, GHG emissions, and biodiversity.

4.1. Water

The water footprints of meat products are substantially larger than those of most plant-based products, nuts being one of the few exceptions (Gerbens-Leenes et al. 2013). Most of the water in livestock production is not required as drinking water for animals but for the production of feed. In fact, more than 97% of the total water footprint in the livestock sector can be traced back to feed production (Mekonnen & Hoekstra 2012). Depending on the feed sources, production systems differ significantly in terms of the quantity and also the type of water used. Ruminants in extensive grazing systems have a very large water footprint, but most of this water is rainwater stored in soils or plants (so-called green water) with low competition for other uses (Gerbens-Leenes et al. 2013). Although green water scarcity is an issue in some regions (Schyns et al. 2019), water competition is often much higher for groundwater or surface water (so-called blue water). In addition, water pollution due to livestock production activities (so-called gray water) can be an issue. Hence, past research has put a much higher emphasis on blue and gray water footprints than green water footprints of different foods.

Considering only blue and gray water, production of beef, poultry, and pork has a similar footprint, while goat and sheep meat have substantially smaller footprints. As issues around water scarcity and water pollution mostly relate to groundwater and surface water, extensive grazing systems are clearly preferable over intensive meat production systems, even though the latter have a smaller total water footprint (including green water). The question of how meat compares with plant-based foods thus hinges on how exactly the meat was produced. For instance, intensively produced pork and beef have more than twice the blue and gray water footprints of cereals and pulses per gram of protein, whereas beef, sheep, and goat meat produced in extensive grazing systems have smaller blue and gray water footprints than cereals and pulses (Gerbens-Leenes et al. 2013).

4.2. Greenhouse Gas Emissions

The food system is a key emitter of the three primary GHGs: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) and is responsible for about one-third of all global anthropogenic GHG emissions (Crippa et al. 2021, Poore & Nemecek 2018). While more GHG emissions emanate from the combustion of fossil fuels, emissions from the food system alone, if unabated, would suffice to thwart the target of keeping global warming below 1.5°C (Clark et al. 2020). This means food system emissions must be reduced substantially and, as meat and other animal-sourced foods account for the largest share of these emissions, the livestock sector is on the spot in particular.

GHG emissions attributable to meat and livestock primarily stem from the production of feed (land use and land-use change), the enteric fermentation in ruminants, and the management of manure. Emissions from transport, packaging, and retail are almost negligible in comparison (Poore & Nemecek 2018). The production of feed is largely associated with CO_2 and to a lesser extent N_2O emissions, whereas enteric fermentation and manure management are mostly associated with CH_4 emissions (Chang et al. 2019, Herrero et al. 2016). These gases have different global warming potential (GWP), so that comparison and aggregation can be complex. CH_4 has a much higher GWP than CO_2 but at the same time is comparatively short-lived. CO_2 has an average atmospheric lifetime beyond 100 years, whereas CH_4 has an average atmospheric lifetime of only 12 years. Stable emissions of CO_2 therefore add cumulatively to the atmospheric stock, while stable emissions of CH_4 can establish an equilibrium where emissions and removals are approximately balanced (Liu et al. 2021, Lynch et al. 2020).

To transform the climate effects of different gases into one comparable unit, past analyses and international climate policy have relied heavily on a metric that scales the GWP of a gas relative to CO_2 for a time span of 100 years (GWP_{100}). According to these calculations, the GWP of CH_4 from the livestock sector is 27.2. When shorter time spans are considered, the GWP of CH_4 increases: For instance, the GWP_{20} of CH_4 is 80.8 (IPCC 2021). Such static metrics, however, cannot properly capture the different dynamics of gases. A more recently developed metric, the GWP^*, is able to describe dynamic responses of different GHGs and assigns CO_2 equivalents that vary over any time frame of interest (Cain et al. 2019, Lynch et al. 2020). Although this method may reflect the GWP of CH_4 better than does static metrics, it is not yet widely used in GHG accounting.

From a consumption perspective, it is interesting to compare GHG emissions per kilogram of product for meat, other animal-sourced foods, and plant-based foods, which is done in **Figure 4*a*** using the common GWP_{100} metric. As illustrated, while GHG emissions differ between meat types and production conditions, all meats are associated with much higher emissions than plant-based foods. The climate footprints of red meat are particularly large, and the emissions from beef raised in extensive grazing herds are larger than those from beef raised in intensive fattening units or from dairy herds. These comparisons clearly underline existing trade-offs between climate protection, water protection, and reducing the food–feed competition. Feeding cattle primarily on roughage that is inedible for humans leads to stronger enteric fermentation and requires more time for an animal to reach a desirable slaughter weight, thus causing higher CH_4 emissions than feeding cattle on higher-quality feeds (Pierrehumbert & Eshel 2015).

It may be argued that a comparison of animal-sourced and plant-based foods per kilogram of product is inappropriate, because animal-sourced foods tend to contain more nutrients, especially

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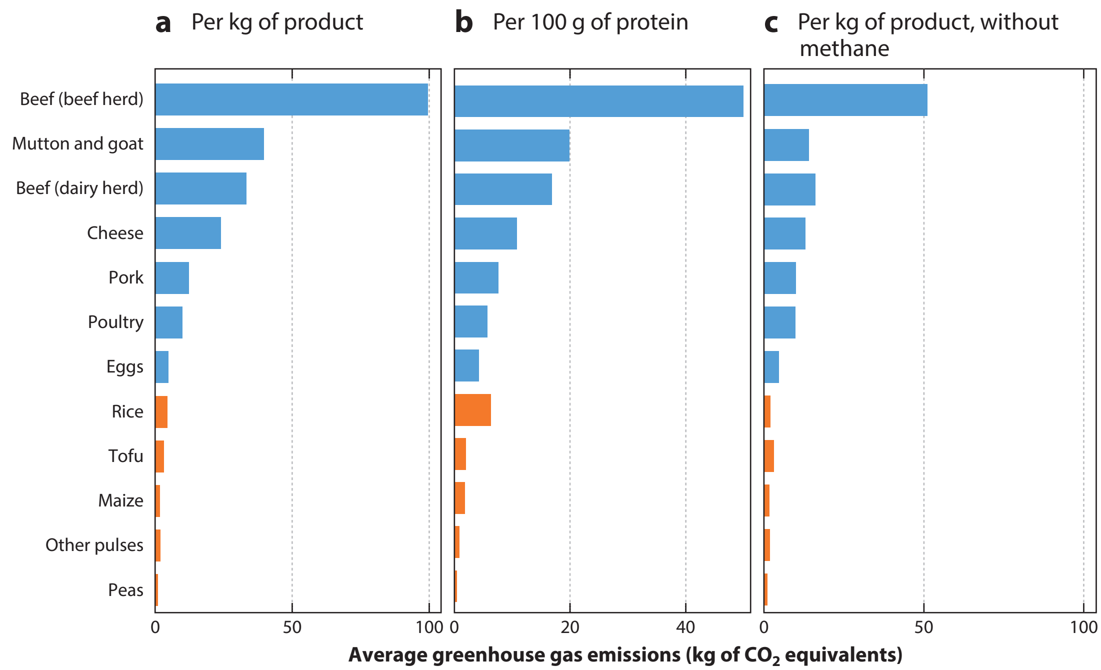

Figure 4

Average greenhouse gas emissions associated with different food products. Animal-sourced foods are shown in blue, plant-based foods in orange. (*a*) Emissions per kilogram of food product, (*b*) emissions per 100 g of protein, and (*c*) emissions per kilogram of product without methane included. Data from Poore & Nemecek (2018), Ritchie (2020), and Ritchie & Roser (2021).

protein. However, also when comparing per unit of protein, the picture that meat has a much larger climate footprint than plant-based foods remains the same (**Figure 4*b***). Finally, as mentioned, there is some debate about how to properly convert CH_4 into CO_2 equivalents. Some may argue that the GWP_{100} of CH_4 is possibly overestimated. But even when not including CH_4 at all into the calculations, which clearly leads to underestimation because the true GWP of CH_4 is certainly greater than zero, all meat types remain significantly more climate intensive than common plant-based foods (**Figure 4*c***). Hence, from a mere climate perspective, vegetarian diets would be preferred over meat-based diets.

The potential of reducing CH_4 emissions from livestock and other sectors for short-run climate change mitigation has recently gained a lot of attention (IPCC 2021, Reisinger & Clark 2018). Key leverage points in the livestock sector would be reducing the number of ruminants globally (Ripple et al. 2014), improved feed digestibility (Herrero et al. 2016), technological advances such as feed additives (Lean et al. 2021), and improvements of animal productivity, including in the small-farm sector (Eisler et al. 2014). Some of these strategies may conflict with other sustainability objectives (Salmon et al. 2018), so better data are needed to understand and manage the trade-offs in different contexts. In any case, CH_4 reductions should not be considered a substitute for CO_2 reductions. The earlier we manage to decarbonize, the larger a future permissible rate of stable CH_4 emissions could be under a given temperature ceiling (Lynch et al. 2020).

Most of the CO_2 emissions from livestock relate to land use and land-use change to produce feed (De Sy et al. 2015, Ripple et al. 2014). For instance, in many parts of the world, forests, bushlands, and peatlands are converted to make space for pastureland or cropland to produce livestock feed. Avoiding such land-use change is one of the key levers of natural climate change mitigation (Bossio et al. 2020). Even when existing pastureland and cropland are used to produce livestock feed, there is a carbon opportunity cost because restoration of native ecosystems could help remove substantial CO_2 from the atmosphere (Hayek et al. 2021, Poore & Nemecek 2018).

Some of the GHG emissions from ruminant production systems can be offset by land-based carbon sequestration, for instance, through certain types of silvo-agro-forestry systems or intensive rotational grazing (Cusack et al. 2021). Well-managed rangelands can store a considerable amount of carbon while producing other positive environmental externalities, such as increased water-holding capacities (Henderson et al. 2015, Machmuller et al. 2015). However, soil carbon sequestration rates heavily rely on suitable agroecological conditions and tend to diminish over time (Cusack et al. 2021, Henderson et al. 2015). Moreover, carbon sequestration in the soil is reversible if the land use changes at some point. It is also important to note that only light grazing intensity actually leads to carbon sequestration, while moderate and heavy grazing instead cause additional CO_2 emissions (Zhou et al. 2017). This does not mean that land-based sequestration strategies tailored to local contexts should not be encouraged, only that the mitigation potential at global scale is likely much lower than what is often claimed. In fact, the grazing systems observed today in many parts of the world are net contributors to climate change (Godde et al. 2020).

4.3. Biodiversity

Land expansion for pastures and cropland is a major contributor to climate change but is also the predominant driver of natural habitat destruction, with serious negative effects on wild biodiversity (Williams et al. 2021). In addition, livestock-related environmental issues such as climate change, water and soil pollution, hunting for bush meat, overgrazing, or disease transfers are serious challenges for biodiversity. Several recent studies conclude that livestock production is one of the leading causes of global biodiversity loss (Crenna et al. 2019, Henry et al. 2019, Machovina et al. 2015). But the nature and severity of different types of biodiversity issues vary geographically. Land expansion is particularly problematic in Latin America and Southeast Asia. Hunting for bushmeat and habitat modification are issues particularly relevant in sub-Saharan Africa and certain parts of Asia. Excessive fertilization of maize and other feed crops occurs in parts of North America, Europe, and Asia but leads to global problems in terms of numerous aquatic dead zones (Diaz & Rosenberg 2008, West et al. 2014). All problems have in common that they lead to loss of species at multiple trophic levels, often with devastating ripple effects on biodiversity and ecosystem functioning.

Of course, livestock producers can also act as valuable stewards of ecosystems. In some cases, meat production may cause positive externalities for wild animals and plant biodiversity, for example, through the provision of nutrients in otherwise barren grasslands or the eradication of certain livestock diseases (Dong et al. 2020, Marshall et al. 2018, Normile 2008, Yuan et al. 2016). Such effects demonstrate that not all types of meat production impede ecosystem functionality. However, such local positive externalities cannot mask the fact that meat production directly contributes to many global biodiversity issues.

5. HEALTH ASPECTS

Malnutrition continues to be a major global concern. Close to 150 million children are stunted, meaning that they are too short for their age, mostly due to low dietary quality and limited access to healthcare (Dev. Initiat. 2021). Around 800 million people lack sufficient access to food energy, and many more suffer from micronutrient deficiencies. Global progress toward ending hunger has recently been stagnating, and the goals of reducing anemia, childhood stunting, and childhood wasting seem to be off track (FAO 2021b). Meat, which contains important macronutrients (mostly protein and fat) and micronutrients, including vitamins and minerals such as iron and zinc, can make important contributions to alleviate nutritional deficiencies. Recent analyses with data from various developing countries show that the consumption of meat and other animal-sourced foods is positively associated with child linear growth, even after controlling for confounding factors such as income and wealth (Headey et al. 2018, Zaharia et al. 2021).

However, positive associations between meat consumption and nutrition and health in some situations do not imply that healthy nutrition without meat would not be possible (Lynch et al. 2018, Melina et al. 2016). Moreover, positive health effects at low to moderate meat consumption levels cannot be assumed to occur proportionately also at higher consumption levels. In fact, at high consumption levels negative health effects may occur, at least for certain types of meat (Yang et al. 2016, Zhang et al. 2021). Finally, meat production may have important health implications. These aspects are discussed in more detail below.

5.1. Meat and Nutrient Adequacy

Nutrient-rich foods such as fruits, vegetables, meat, and other animal-sourced products are usually costlier than calorie-dense staple foods. Hence, nutrient-adequate diets are substantially more expensive than simple calorie-sufficient diets (Bai et al. 2021, Herforth et al. 2020). It is estimated that globally more than 1.5 billion people cannot afford diets that are nutrient-adequate (Herforth et al. 2020, Hirvonen et al. 2020).

Recent research and modeling exercises have analyzed nutrient-adequate diets and their costs in different country contexts using local average prices (Bai et al. 2021, Chungchunlam et al. 2020). One objective of this research is to identify lowest-cost healthy diets, which can be useful to develop strategies and dietary recommendations for poor households and communities. Results suggest that lowest-cost healthy diets rarely contain any meat, because meat is not a cheap source of nutrients on average. However, existing studies on lowest-cost healthy diets have a few shortcomings. They typically use aggregated retail prices, do not automatically produce realistic diets, and often fail to account for important nutrient additivity and interaction effects (Moughan 2020). Also, existing studies are mostly based on the nutritional requirements of a representative adult person and may not properly account for local environments and price seasonality.

In many contexts, meat therefore plays a larger role in actual diets than what lowest-cost healthy diet calculations would suggest, even among poor households. This often applies to small-farm contexts in developing countries where people derive meat from multifunctional livestock, such as meat from animals previously used for draught power or milk production or as informal insurance. A recent study with data from various countries in Africa shows that livestock production is positively associated with child and adolescent nutrition in smallholder farm households (Khonje et al. 2022). Meat can also be important for people with little access to sufficient plant-based alternatives, especially in remote and dry rural areas where year-round crop production is difficult and where food markets are not functioning well. Fruits and vegetables in particular often suffer from severe price seasonality. In comparison, animal-sourced foods are much less prone to price seasonality and can therefore be more stable sources of key micronutrients (Bai et al. 2020).

Given that meat is a rich source of essential amino acids and micronutrients, it can also help reduce nutritional deficiencies among people with limited knowledge about nutrient requirements and how to meet them through diverse plant-based diets. While this holds true for poor population segments with low educational levels in general, it is particularly relevant for groups with specific nutrient requirements, such as children, pregnant and lactating women, and people with certain allergies or intolerances. Nutritional requirements can mostly be met with vegetarian diets for these groups as well, but the planning is much more complex, especially in poor communities. Several empirical studies with data from various countries confirm that the likelihood of nutritional deficiencies in children, adolescents, and adults decreases significantly with meat included in the diet (Headey et al. 2018, Khonje et al. 2020, Leroy & Cofnas 2020, Papier et al. 2021, Zaharia et al. 2021).

5.2. Meat and Various Health Outcomes

Beyond the effects of meat consumption on nutrient adequacy, numerous studies have also linked the consumption of different types of meat to various diseases. Possible negative health effects of consuming processed red meat and red meat more generally have recently become the focus of international debates. Several meta-analyses covering observational studies and also a few randomized controlled trials suggest that the consumption of processed red meat, which usually refers to meat from beef, lamb, pork, or game preserved by smoking, curing, salting, or adding chemical preservatives, is associated with increased risk of type 2 diabetes (Micha et al. 2012, Pan et al. 2013), cardiovascular diseases (Micha et al. 2010, Yang et al. 2016), dementia (Zhang et al. 2021), and several types of cancer, most notably colorectal cancer (Lippi et al. 2016). While these meta-analyses do not provide conclusive proof of causality, they still strongly suggest that a direct link between processed red meat consumption and several health risks is likely.

These results for processed red meat cannot simply be extrapolated to other types of meat. In fact, for other types of meat, studies suggesting positive health associations also exist, even beyond the nutrient adequacy mechanisms described above. For instance, the consumption of unprocessed red meat has been associated with lower risk of dementia (Zhang et al. 2021). The consumption of poultry has been associated with lower risk of some types of cancer (Lippi et al. 2016). Meat eaters may also have better bone health on average and thus a lower risk of certain site-specific bone fractures (Tong et al. 2020). One possible reason for the comparatively poor record of processed meat with regard to health aspects including cardiovascular diseases is the higher sodium content of processed red meat compared to other types of meat (Micha et al. 2010, Delgado et al. 2021). Concerning mental health, a recent systematic review suggests that the exclusion of meat from the diet is associated with increased risk of depression and anxiety (Dobersek et al. 2021), even though this association may not be unique for meat, as depressive symptoms were also shown to be associated with the exclusion of other food groups from people's diets (Matta et al. 2018).

All of these studies encounter methodological challenges, making it difficult to establish clear causality. Longitudinal studies with observational data suffer from potential confounding effects through other dietary or nondietary factors. For instance, the identified associations are often substantially attenuated when controlling for body mass index (Papier et al. 2021, Tong et al. 2020). Further, issues of reverse causality can arise. Health-conscious people may choose more plant-based diets in the first place. People with mental disorders may be more concerned about animal suffering, meaning that the abstention from meat could reflect self-protective behavior (Michalak et al. 2012). Recall bias or measurement error in dietary assessments can sometimes be another methodological challenge. Randomized controlled trials reduce some of these methodological challenges, but they are rarely able to study long-term health effects. Moreover, results typically hinge on the type of food used in the trials to replace meat. For instance, associations between red meat consumption and cardiovascular risk factors seem to be quite sensitive to whether the replacement diet consists of high-quality plant protein sources, mixed animal protein sources including dairy, carbohydrates, or usual diets (Guasch-Ferré et al. 2019).

Given these complexities, recommending specific maximum levels of meat consumption purely based on health criteria is difficult or impossible (Leroy & Cofnas 2020). Even if one accepts that increased consumption of some meat types causally increases certain health risks, exact dose-response relationships remain uncertain. In general, the consumption of small to moderate quantities of meat is widely seen as unproblematic or even positive for human health. One exception is processed red meat, where meta-analyses suggest that even small quantities can be associated with negative health effects, such as higher risk of cancer mortality (Wang et al. 2016).

For high meat consumption levels, the evidence of negative health effects is stronger, which is true for all types of meat but again especially for red meat (processed and unprocessed) and processed meat. Nevertheless, these health effects need to be seen in perspective. Global Burden of Disease data show that dietary risk factors account for a large share of the total health burden in rich and poor countries alike. But among the different dietary risk factors—also including excessive sodium and sugar intakes—high meat consumption is not the dominant one. In high-income countries, the health burden from excessive sodium consumption is three times larger than the health burden from excessive meat consumption. In low- and middle-income countries the health burden from excessive sodium consumption is even 30 times larger (Afshin et al. 2019).

Overall, for low-income populations that often primarily consume starchy staple foods and suffer from various nutritional deficiencies, the consumption of small to moderate quantities of meat and other animal-sourced foods should be promoted rather than discouraged from a health perspective (Adesogan et al. 2020, Herforth et al. 2019, Nordhagen et al. 2020). In contrast, the average quantities of meat consumed in most high-income countries are hardly justifiable from a nutrition and health perspective. In rich countries, notable reductions in meat consumption would have positive health and environmental effects alike.

5.3. Health Effects from Production

The previous subsections analyzed possible health effects of meat consumption, but the production of meat can also have health effects, and most of these are negative. Air quality–related health harms associated with particulate matter emissions from meat production facilities were already discussed above in connection with environmental issues (Domingo et al. 2021). In addition, workers in the meat processing sector are particularly often exposed to various physical and mental occupational health hazards related to sharp knives, air quality problems, stress, and generally poor working conditions (van Cleef et al. 2010, Ramos et al. 2021). Slaughterhouses and meatpacking facilities have also been associated with the emergence or outbreaks of various zoonotic diseases, including swine flu, avian influenza, and COVID-19 (Middleton et al. 2020, Moore et al. 2021). The widespread use of antibiotics in intensive meat production systems is also associated with the risk of resistance development in pathogen populations, reducing the effectiveness of antibiotics in medical applications (van Boeckel et al. 2015).

More generally, livestock play a critical role in the transmission and spread of diseases from animals to humans, whereby wild animals are often the primary hosts and farm animals the amplifying hosts. On the one hand, traditional production systems such as backyard farming or bushmeat hunting tend to raise the risk of animal-to-human transmission (Naguib et al. 2021). Intensive livestock systems, on the other hand, often exacerbate the impact of diseases due to high densities of genetically similar animals, increased immunodeficiencies, and the transport of live animals over longer distances, the latter of which is still common in many places (Espinosa et al. 2020, Gilbert et al. 2015, Grace et al. 2017). The global economic burden of zoonotic diseases had been pointed out even before the COVID-19 pandemic (Gebreyes et al. 2014). Given that current efforts to mitigate the emergence and spread of zoonoses hardly match the rates of livestock intensification in low- and middle-income countries, related health problems are likely to grow in the future (Gilbert et al. 2021).

6. ETHICS AND ANIMAL WELFARE

Meat consumption is not possible without killing animals. In 2018, more than 70 billion land animals were slaughtered worldwide to produce meat for human consumption. Keeping animals just for the purpose of slaughtering them raises potential concerns. The way animals are kept can also raise ethical issues (Grethe 2017). People's animal welfare concerns seem to increase with economic and social development, which is why animal welfare is discussed here as a relevant dimension of sustainability.

6.1. Evolving Ethical Concerns

Ethical considerations around meat production and consumption depend on which moral standing societies award to nonhuman creatures, which can differ culturally and can change over time. The ethics of meat consumption can be assessed through two distinct approaches, the dietetic and the productionist (Thompson 2017). The dietetic approach asks if meat production and consumption are ethically acceptable at all. For a long time, the prevailing anthropocentric view that animals were made for human's use left no doubt that humans are allowed to keep, use, and eat animals. First ethical concerns about meat consumption based on a sense of human responsibility for animals and a resulting injustice and harm coming from slaughter can be traced back to Jain and Buddhist concepts in ancient India around 600 BC and to the ancient Greeks around 500 BC. Since then, several religions and secular movements have called for the complete abstention from meat consumption based on ethical grounds (Leitzmann 2014). The productionist approach is less radical and addresses the potential for ethically motivated changes in terms of how and under what conditions meat is produced and consumed (Thompson 2017).

Regardless of the particular approach, most ethical arguments around meat build on the premise that the suffering and harm done to animals should be reduced. Animal welfare concerns tend to increase with people's education and income levels and are therefore more pronounced in high-income countries compared to low- and middle-income countries. Studies also suggest that women are more concerned about animal welfare issues than men, and younger people more than older ones (Alonso et al. 2020).

It is estimated that so far less than 1% of the world population considers the consumption of meat and other animal-sourced products as unethical per se (Alonso et al. 2020). Globally, around 1.5 billion people are vegetarian, but only 75 million of them are assumed to be vegetarian by choice; the rest does not consume because meat is unavailable or unaffordable (Leahy et al. 2010). And of those who are vegetarian by choice, ethical considerations are not the only reason; environmental and climate concerns also seem to be important factors for many to refrain from meat consumption. Nevertheless, as mentioned, ethical concerns seem to be increasing.

6.2. Animal Welfare Issues

Animal welfare concerns generally relate to one or more of four domains, namely livestock nutrition, environment, health, and behavior. Most of the debate focuses on intensive and industrial systems of meat production (Temple & Manteca 2020, Thompson 2017). In these systems, animal welfare issues commonly raised relate to high stocking density, prophylactic use of antibiotics, purely performance-driven breeding objectives, lack of variation in climate and floor covering, and limited access to natural activities (Clark et al. 2016, Grethe 2017). Other concerns are more species specific, such as tail docking of pigs, beak trimming of poultry, or dehorning of cattle.

Intensive livestock production systems are similar across world regions, without clear differences in terms of key animal welfare issues. However, people's concerns about these issues seem to be most pronounced in Northwestern Europe. Countries in North America and Oceania have similar public debates, yet often occurring with a certain time lag and with lower ferocity than in Northwestern Europe (Busch & Spiller 2018). People in Southern Europe are often more concerned about meat quality rather than animal welfare issues as such, even though quality is often related to husbandry conditions (Alonso et al. 2020). Studies about animal welfare concerns in developing countries are rare.

In extensive husbandry and grazing systems, animals typically live in more natural environments so that welfare issues are of lower concern, especially with respect to the behavioral domain. However, extensive systems may be associated with thermal stress, lower access to feed, water, and veterinary services, and the presence of predators. As extensive systems can be quite diverse, the local relevance of concrete animal welfare issues differs by context (Temple & Manteca 2020). In any case, the general presumption that animals raised in smaller-scale and less-intensive production systems would always enjoy higher levels of animal welfare is incorrect (Grethe 2017, Robbins et al. 2016). Regulatory frameworks as well as ability and motivation of the livestock keeper can be more important factors for animal welfare than herd size or stocking density as such.

Efforts to improve husbandry systems and animal welfare typically involve additional costs that have to be borne by somebody, including meat producers, meat consumers, or taxpayers (Lusk & Norwood 2011). Animal welfare goals may also conflict with other sustainability dimensions. For instance, longer lives of animals, free-range husbandry systems, or lower-quality feed that is not in direct competition with human food all come with productivity declines that can be associated with larger environmental and climate footprints, unless meat consumption is substantially reduced. To underline this point, the GHG emissions per kilogram of beef are six times higher when beef is produced in extensive grassland systems instead of in intensive feedlots (FAO 2021a).

The question of which animal welfare issues to address with highest priority and through what type of interventions is therefore fairly complex. Research shows that consumers often have a positive but limited willingness to pay for higher animal welfare standards (Hartmann & Siegrist 2020). The discrepancy between society's wishes and people's actual purchasing decisions is referred to as the consumer-citizen gap, which makes purely market-based solutions through voluntary standards and labels difficult (Lundmark et al. 2018). Stricter government standards would therefore be required but could only be effective when harmonized internationally; otherwise what's known as low animal welfare havens would likely emerge in an open trading system (Grethe 2007). As an alternative or a complement to government standards, self-regulation mechanisms of the increasingly concentrated food retail sector could be useful to promote socially acceptable forms of livestock production in countries where animal welfare concerns are widespread (Busch & Spiller 2018).

7. TOWARD MORE SUSTAINABLE SCENARIOS

The previous sections have shown that current meat consumption levels are not compatible with sustainable food systems. At the global level, meat demand continues to grow quite rapidly, which could have disastrous consequences for planetary health over the next few decades (Hayek et al. 2021, Springmann et al. 2018a, Williams et al. 2021). At the same time, meat is an integral part of our food system that can help reduce poverty and widespread nutritional deficiencies, especially in low- and middle-income countries. Finding sustainable solutions to this dilemma is a central food systems challenge that needs to be addressed.

For each sustainability dimension, various potential approaches exist to improve the situation, but most of these approaches come with trade-offs with respect to other sustainability dimensions. For instance, efficiency gains through further intensification could reduce the climate footprint of meat production and also lower the demand for agricultural land, but they would likely increase issues of point source pollution, eutrophication, zoonotic diseases, and animal welfare (Röös et al. 2017). Intensification in large-scale meat production units could also be associated with negative social effects for smallholder livestock keepers in developing countries (Baltenweck et al. 2020). Various technological options to reduce existing trade-offs in meat production could be developed but alone will likely not suffice for staying within planetary boundaries, especially not with respect to climate targets (Clark et al. 2020, Springmann et al. 2018a). Hence, notable changes in meat consumption will also be required.

7.1. Technological Improvements in Meat Production

Most sustainability issues around meat occur at the level of production; therefore, the continuous development of better technologies to reduce these issues is a logical and important strategy. Gains in productivity and efficiency of meat production have large potential to reduce the use of scarce natural resources per unit of output and could be achieved through improvements in animal genetics, nutrition, and health. This is especially true in regions where livestock productivity is currently low, such as Africa and parts of Asia (Enahoro et al. 2019). Africa and Asia are also the regions where climate change will likely have the most severe negative effects on livestock supply chains, such that novel technological solutions are also needed from a climate adaptation perspective (Godde et al. 2021). Given the important social dimension of livestock in developing countries, technology strategies in these contexts should not only focus on average results but should also consider distributional effects (Salmon et al. 2018).

Farm management and agricultural and food policies are evolving all over the world; in many countries, certain steps toward higher levels of sustainability have already been taken. Yet, further changes are urgently needed for more sustainable meat production. Various interesting techniques and practices such as improved manure management to reduce emissions or improved grazing to increase soil sequestration exist, but their current use is still only a small fraction of what is technically possible, mainly owing to economic adoption constraints (Herrero et al. 2016). More research is needed to identify the most promising management options and how to implement them at scale in different agroecological and socioeconomic contexts.

Researchers are also working on novel technologies and approaches, some of which are already being implemented. The addition of insects, seaweed, and other additives to livestock feed can reduce GHG emissions and ease the competition with human food (Herrero et al. 2016). Digital devices to track or confine livestock, genome editing to develop new breeds combining high productivity with resistance to various biotic and abiotic stresses, early warning systems for pests and diseases, novel types of livestock vaccines, or prebirth sex determination technologies are other areas of innovation that could substantially gain in importance in the years to come. Research on potential risks to avoid undesirable side effects is certainly important, as is transparent communication to gain public trust and acceptance (Herrero et al. 2020).

Another area that has recently gained a lot of public attention is the development of lab-grown (cultured) meat. Lab-grown meat is sometimes hyped as a food revolution that could bypass the environmental and animal welfare issues of conventional meat production (Dolgin 2020). Unquestionably, lab-grown meat has interesting potential, but the research is still at the experimental stage and many potential issues remain unresolved. Animals will still need to be kept to harvest cell source material for in vitro cultivation, and feed will still need to be produced for effective cell growth and propagation. Therefore, lab-grown meat's actual contribution toward key sustainability dimensions remains uncertain (Rubio et al. 2020, van der Weele et al. 2019). Existing methods of lab-grown meat are not yet economically viable. Moreover, control of the nutritional composition is still unclear, especially for iron and other micronutrients (Chriki & Hocquette 2020). There are also potential issues of public acceptance, as lab-grown meat may possibly not align well with religious rules and many food consumers' preferences for naturalness. Finally, lab-grown meat will have to compete with various plant-based meat alternatives and other protein sources, for which predicting long-term developments of consumer preferences is equally difficult.

7.2. Changes in Meat Consumption

In spite of likely technological improvements in meat production, changes in meat consumption will also be necessary to make food systems more sustainable. Given that plant-based diets have much smaller environmental and climate footprints, substantial reductions in average meat consumption will be needed in regions that currently have high consumption levels, which is true in most high-income and several middle-income countries. This does not mean that everybody would need to become vegetarian or even vegan. Low and moderate meat consumption levels are compatible with the climate targets and broader sustainable development, even for 10 billion people (Muller et al. 2017, Willett et al. 2019). In low-income countries, increases in the consumption of meat and other animal-sourced foods could help reduce nutritional deficiencies and promote human health, especially among vulnerable groups such as children, adolescents, and pregnant and lactating women (Adesogan et al. 2020, Khonje et al. 2020, Nordhagen et al. 2020).

While increases in meat consumption among poor and vulnerable groups will require improvements in technology, income, and market functioning, notable reductions in meat consumption in richer countries require behavioral changes that are not easy to enforce and will take time. Education and awareness building are important strategies to promote more sustainable consumption styles. Other types of policy interventions are possible to accelerate this process but are likely more controversial in democratic societies (Rust et al. 2020, Valli et al. 2019). Of course, the protection of consumers' sovereignty is an important objective, but state interventions could be justified on the basis of negative environmental and health externalities (Bonnet et al. 2020, Moran 2021, Springmann et al. 2016). The concrete types of interventions that would be most useful to reduce high meat consumption levels are not yet well understood (Resare Sahlin et al. 2020).

Soft interventions such as education, product labeling, and certain forms of nudging are socially more acceptable but tend to have relatively small effects on dietary choices (Diepeveen et al. 2013, Edenbrandt & Lagerkvist 2021, Uehleke & Hüttel 2019). However, with a smart design the effectiveness of such soft interventions may increase, so more research and experimentation would be useful (Vainio 2019). Consumers' awareness for sustainable nutrition could also be influenced through revised dietary guidelines; so far, food-based dietary guidelines in most countries do not explicitly include aspects of planetary health (Herforth et al. 2019). A study with data from the United States shows that balanced plant-based diets outperform other diets based on national dietary guidelines in terms of most sustainability dimensions (Blackstone et al. 2018).

More intrusive methods to reduce meat consumption include restrictions or fiscal mechanisms such as taxes. Even though consumption taxes are a relatively blunt instrument, many studies argue that meat is significantly underpriced in most rich countries due to significant subsidies and negative externalities (Giubilini et al. 2017, Katare et al. 2020, Springmann et al. 2018b). A tax on meat consumption could reduce these externalities without jeopardizing the competitiveness of domestic producers, as a consumption tax would not differentiate between domestically produced and imported meat. Tax revenues could be used to promote research aimed at increasing the sustainability of meat production and to cushion social hardships among low-income consumers (Katare et al. 2020, Säll 2018). More research on behavioral responses to higher meat prices would be useful to guide policymaking on appropriate taxing strategies (Hestermann et al. 2020).

The reduction of meat in people's diets, where appropriate, needs to be accompanied by an increase in alternative sources of protein and micronutrients to avoid nutritional deficiencies. Dairy products and eggs contain many relevant nutrients but also have larger environmental and climate footprints than plant-based alternatives. Pulses are a rich source of protein, whereas fruits and vegetables are good sources of several micronutrients. Plant-based dietary recommendations typically also include more whole grains as well as nuts and seeds (Willett et al. 2019). Insects and algae might gain in importance, depending on consumer acceptance and technological improvements to produce and harvest at scale. High-tech products, such as lab-grown meat and ultraprocessed plant-based meat alternatives are currently getting a lot of public attention, but their role in promoting balanced, healthy, and sustainable nutrition at scale is still uncertain (van der Weele et al. 2019, van Vliet et al. 2021).

Overall, a transition toward more sustainable scenarios of meat production and consumption requires multiple approaches, always adjusted to local environmental, economic, and social conditions. New technologies, improved policies and institutions, and behavioral changes among consumers and other food systems actors will all be needed for rapid progress. Profound changes can only be achieved when the overall goals and directions are broadly shared by society. This will require serious engagement with all relevant stakeholders, including farmers, consumers, researchers, politicians, regulatory bodies, nongovernmental organizations, and the food industry (Lazarus et al. 2021, Rust et al. 2020).

8. CONCLUSION

Global meat consumption continues to rise, especially in low- and middle-income countries where average per capita consumption levels are still much lower than in most high-income countries. Meat production requires more land and water than the production of plant-based foods and has much larger environmental and climate footprints. Hence, against the backdrop of planetary boundaries, high and further rising meat consumption levels are worrisome. Intensive meat production and excessive meat consumption can also be associated with negative effects on human health and animal welfare. Therefore, notable reductions in meat consumption levels would be useful and important in terms of various sustainability dimensions, at least in high-income countries. In low- and middle-income countries, more nuance is required. Meat is a rich source of various nutrients, so including it in local diets can help reduce widespread nutritional deficiencies and promote human health, especially where nutritious plant-based alternatives are not available or affordable year-round. For many poor people in developing countries, meat and livestock production is also an important source of income and a provider of several other social functions.

While high meat consumption levels for all are not compatible with sustainable development, low to moderate consumption levels are compatible, even for a world population of 10 billion people (Willett et al. 2019). This means that significant reductions in meat consumption are required in some regions, whereas certain increases could be useful in others. How to effectively change consumer behavior and reduce meat consumption where needed remain open questions. Education and awareness building will have an important role to play, but fiscal policies to internalize some of the major externalities may also be needed (Pieper et al. 2020).

In addition to changes on the consumption side, technological improvements are needed to make meat and livestock production more sustainable. Various technological options to improve animal genetics as well as feed and husbandry systems are available and need to be further developed and implemented at scale. Technology must also play an important role to further develop meat alternatives for healthy nutrition with much lower environmental and climate footprints. All of these approaches need to be pursued in parallel. Transitioning toward more sustainable food systems requires multiple behavioral, institutional, and technological changes at various levels (von Braun et al. 2021). More economics research is needed to guide this transition in terms of developing suitable policies and incentive mechanisms considering all relevant sustainability dimensions.

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