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Critical Review

Friend or Foe? The Role of Animal-Source Foods in Healthy and Environmentally Sustainable Diets

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ABSTRACT

Scientific and political discussions around the role of animal-source foods (ASFs) in healthy and environmentally sustainable diets are often polarizing. To bring clarity to this important topic, we critically reviewed the evidence on the health and environmental benefits and risks of ASFs, focusing on primary trade-offs and tensions, and summarized the evidence on alternative proteins and protein-rich foods. ASFs are rich in bioavailable nutrients commonly lacking globally and can make important contributions to food and nutrition security. Many populations in Sub-Saharan Africa and South Asia could benefit from increased consumption of ASFs through improved nutrient intakes and reduced undernutrition. Where consumption is high, processed meat should be limited, and red meat and saturated fat should be moderated to lower noncommunicable disease risk—this could also have cobenefits for environmental sustainability. ASF production generally has a large environmental impact; yet, when produced at the appropriate scale and in accordance with local ecosystems and contexts, ASFs can play an important role in circular and diverse agroecosystems that, in certain circumstances, can help restore biodiversity and degraded land and mitigate greenhouse gas emissions from food production. The amount and type of ASF that is healthy and environmentally sustainable will depend on the local context and health priorities and will change over time as populations develop, nutritional concerns evolve, and alternative foods from new technologies become more available and acceptable. Efforts by governments and civil society organizations to increase or decrease ASF consumption should be considered in light of the nutritional and environmental needs and risks in the local context and, importantly, integrally involve the local stakeholders impacted by any changes. Policies, programs, and incentives are needed to ensure best practices in production, curb excess consumption where high, and sustainably increase consumption where low.

Keywords: animal-source foods, livestock, nutrition, health, environmental sustainability

Introduction

Animal-source foods (ASFs) are derived from animals, which are broadly categorized into meat, fish (including all aquatic ASFs), eggs, and dairy. ASFs are distinct from plant-source foods (PSFs), which include all foods derived from plants, such as pulses, roots, nuts, seeds, grains, fruit, aquatic plants, vegetables, and fungi, such as mushrooms, even though they do not belong to the plant kingdom. Although this simplification hides enormous heterogeneity, it can be useful for organizing bodies of evidence and guiding programs, policies, and incentives.

ASF consumption varies widely by food group, geography, income, and education. Individuals in Central or Eastern Europe, Central Asia, and high-income countries consume the most amounts of ASFs, whereas individuals in South Asia and Sub-Saharan Africa consume the least amounts ASFs [1]. ASF consumption is generally highest among urban, high-income, and educated populations, with few exceptions [1].

ASFs are known to have both positive and negative health consequences; yet, policy guidelines on intake levels are limited. Health and nutrition researchers have implicated ASFs in diet-related noncommunicable diseases (NCDs) (including obesity,

Abbreviations: ASF, animal-source food; EAA, essential amino acid; GHG, greenhouse gas; IPCC, Intergovermental Panel on Climate Change; LMICs, low- and middle-income countries; NCD, noncommunicable disease; PSF, plant-source food; WRA, women of reproductive age.

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cardiovascular diseases, diabetes, and certain cancers), indicating that excess consumption of processed meat, red meat, and saturated fat may increase the NCD risk [2, 3]. Similarly, environmental scientists have noted that the production of ASFs can cause substantial negative environmental impacts related to land use, soil health, water quantity and quality, biodiversity, and climate change [4–8]. At the same time, ASFs are rich in commonly lacking nutrients, and increasing their consumption in low- and middle-income countries (LMICs) particularly is a key strategy for addressing undernutrition (including stunting, wasting, and micronutrient deficiencies) [6, 7]. For these reasons, scientists across fields are increasingly debating the role of ASFs in healthy and environmentally sustainable diets [4–7, 9]. Public health guidance on ASFs is also often ambiguous: 98 countries have food-based dietary guidelines; yet, most of them lack recommendations on specific minimum or maximum intake of ASFs [10, 11].

These trade-offs and tensions between nutritional and environmental aspects of ASFs are the focus of this article, which is geared toward a diverse audience, ranging from researchers (across fields) and academics to policymakers, donors, and civil society. We first discuss the health benefits of ASFs and their health risks, and then, we turn to the environmental benefits and risks. Finally, we consider the role of alternative proteins and protein-rich foods (including both health and environmental considerations). Although animal welfare, livelihoods, antimicrobial resistance, and food safety are also important considerations for the role of ASFs in healthy and sustainable food systems, here, we focus on what we consider to be the primary nutritional and environmental issues.

Health Benefits

Health benefits from ASFs stem from their nutritional composition and vary by life course stage. We begin this section by considering the nutritional composition of ASFs and then discuss how the importance of ASFs in diets may vary by life course stage. Foods consist of more than just nutrients, and the whole food matrix and the diverse compounds it contains have holistic effects on human health [12, 13]. However, here, we focus primarily on single nutrients for simplicity and greater evidence availability.

Nutritional composition

ASFs are dense in bioavailable vitamins and minerals. ASFs are the only intrinsic food source of vitamin B12 [7] and contain more bioavailable forms of vitamins A and D, iron, and zinc than PSFs (Figure 1). Deficiencies of these micronutrients during critical periods of the life course can have severe and lasting consequences, including birth defects, anemia, reduced growth, cognitive impairment, increased susceptibility to infections, rickets, decreased work productivity, blindness, and even death [14].

Considering vitamin D, although the body can synthesize it from sunlight, many people are still deficient in vitamin D worldwide, and ASFs such as fatty fish contain the highest amounts of vitamin D [15]. For vitamin A, precursors (carotenoids) such as beta-carotene are available in PSFs but are converted into retinol at a 12:1 ratio on average, with variation in this efficiency across foods and individuals [16]. Importantly, some individuals are poor converters of carotenoids and likely to be

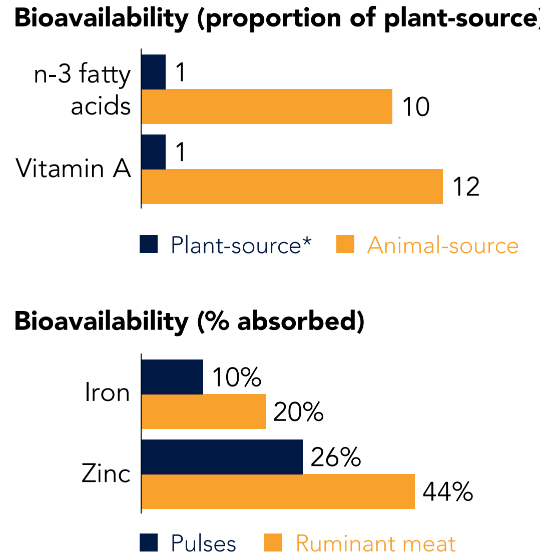

FIGURE 1. Nutrient bioavailability differences between plant and animal sources. *Only terrestrial plant sources of n–3 fatty acids are shown here; sea vegetables contain long-chain n–3 fatty acids and have similar bioavailability as that of animal sources. Bioavailability estimates of n–3 fatty acids [26], vitamin A [16], and iron and zinc [18].

vitamin A–deficient without consuming retinol from ASFs or supplements [17]. However, carotenoids are abundant in many PSFs, and consumption of adequate dark green leafy vegetables and deep red–, orange-, and yellow-fleshed fruits, vegetables, and tubers can be enough to meet the recommended vitamin A intakes for most people, even with little, if any, ASFs [18]. In the case of choline, which can be lacking in the diet even in high-income countries, ASFs, especially organ meats and eggs, contain the highest concentrations of choline [19].

Regarding iron, ASFs contain heme iron (with ~26% to 68% of the iron being heme, depending on the ASF) [18] and no iron inhibiters; PSFs lack heme iron and contain inhibitors. As a result, the iron in ASFs is generally between 1.5 and 2 times more bioavailable than that in PSFs [18]. Nonheme iron is available in PSFs but only between 2% and 20% is absorbed; conversely, 15%–35% of heme iron is absorbed [20]. Higher intakes of unprocessed red meat and poultry meat have been associated with lower risk for iron deficiency anemia [21]. For zinc, antinutrients in PSFs can also inhibit absorption, particularly phytic acid, which is highest in pulses, whole grains, nuts, and seeds [18]. Thus studies have estimated that zinc in ASFs is ~1.7 times more bioavailable than that in most PSFs (Figure 1) [18]. Low meat intake has been associated with reduced zinc intake and retention, even when replaced with zinc-rich PSFs [22]. Restriction or exclusion of ASFs, particularly dairy, is also associated with inadequate calcium intake [23]. Among PSFs, only dark green leafy vegetables and seeds are high in calcium [18]. Although calcium bioavailability in dark green leafy vegetables is similar to that in ASFs [24], some people struggle to meet the recommended calcium intakes without ASFs because of dietary preferences and inadequate food access [23]. However, countries with low milk intake (as well as calcium) do not have high rates of osteoporotic fractures, suggesting that dairy is not an essential food group and the recommended intakes of calcium may not be appropriate [25].

Beyond vitamins and minerals, ASFs also contain essential fatty acids and high densities of amino acids that are important for growth, development, and health maintenance. Fish and other aquatic animals are rich in long-chain n–3 fatty acids: DHA and EPA, which are essential for fetal development and healthy aging [26]. Sea vegetables contain DHA and EPA; however, all other PSFs lack these fatty acids and instead contain high concentrations of ALA, of which ≤10% is converted into DHA and EPA (Figure 1) [26]. Thus, restriction or exclusion of ASFs requires adequate consumption of sea vegetables—a rarity outside of East Asia—or much higher intakes of n–3 fatty acids from terrestrial PSFs.

ASFs generally contain higher densities and more bioavailable forms of essential amino acids (EAAs) than those contained in PSFs [27]. For example, the digestible indispensable amino acid score is much higher for ASFs than that for most PSFs, except for certain soy products (Figure 2). Because of the limiting proportions of specific EAAs in plants (e.g., lysine in grains and methionine in beans), restriction or exclusion of ASFs, particularly on a lower-protein diet, requires daily consumption of foods with complementary EAA profiles (e.g., combining beans and rice). Populations with limited access to adequate energy intake, ASFs, or diverse diets are at risk of deficiencies in EAAs [28]. Importantly, protein quality is just one nutritional metric; it should not be overemphasized but rather considered in the broader dietary context and alongside other nutritional components of protein-rich foods (e.g., micronutrient and fiber content and fatty acid profile) [7, 29].

ASFs also contain unique bioactive compounds that may play important roles in health and disease, including creatine, anserine, taurine, cysteamine, 4-hydroxyproline, carnosine, conjugated linoleic acid, certain bioactive peptides, and many others [6, 7]. Previous research has showed that these factors play key roles in anti-inflammatory and immune pathways, memory and cognition, and cardiovascular health, among others [6, 7]. Thus, to summarize, ASFs contain both essential nutrients and bioactive compounds that play vital roles in human health, and in some cases, these constituents are not found in PSFs.

Life course

Nutritional needs vary across the life course to support changing physiological functions, such as growth and development, reproduction, or general health maintenance. There are particular periods when nutritional demands increase, placing an individual at risk when dietary inadequacies arise. For example, inadequate nutrition during the first 1000 d can have severe and lasting consequences, including poor growth and development, increased likelihood of intergenerational malnutrition, decreased economic potential, and increased risk of death [30]. Women of reproductive age (WRA), adolescents, and older adults also have increased nutritional requirements that may be supported by ASFs. For example, dietary iron requirements increase for WRA to compensate for losses during menstruation, and adolescents enter another rapid growth and development phase, thereby necessitating increases in multiple nutrients [31, 32]. There are shifting nutritional needs for older adults to preserve muscle mass, bone health, and cognition [33]. Although ASFs can play a role in healthy diets across the lifespan, we focus on life phases for which ASFs are particularly important: pregnant and lactating women, infants and young children, and, to some extent WRA, adolescents and older adults.

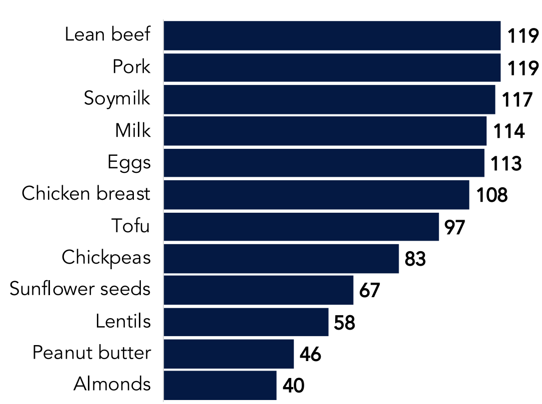

FIGURE 2. Digestible indispensable amino acids scores (DIAASs) of select foods: beef and pork [220], soy milk and tofu [221], and all other foods [222]. DIAASs reflects the percentage of total daily requirement of the most limiting dietary indispensable amino acids contained in an amount of protein equivalent to the estimated average requirement for total daily protein intake of the test protein.

First, considering pregnancy and lactation, ASFs make important nutritional contributions during these periods when women are at increased risk of low or excess weight gain, nutrient deficiencies, and inadequate fetal nutrition. Nutrient requirements increase considerably during pregnancy and lactation. For example, the recommended iron intakes during pregnancy are 1.5 times greater than those for nonpregnant, nonlactating WRA [16]. This continues during lactation, and poor nutrient status and inadequate dietary intakes during lactation can affect the concentrations of certain nutrients in breast milk, including vitamin B12, choline, and lipids contained in ASFs [34]. Even nonpregnant WRA more broadly have increased iron requirements because of losses during menstruation, >2 times those of men [16]. Yet, globally, WRA commonly consume insufficient amounts of iron and zinc [14], 2 critical minerals essential for fetal growth and development [35].

Iron and zinc are found in the highest densities and most bioavailable forms in ASFs such as organ meats, bivalves, and ruminant meat [18]. Thus, such foods can play an important role in addressing these deficiencies. For example, the prevalence of iron deficiency among WRA in the United States rose from 13% in 2004 to 20% in 2016 [36], which may have been due in part to a 15% decrease in beef intake over a similar period [37]. Additionally, moderating the intake of phytate (which inhibits mineral absorption) through fermenting, soaking, or sprouting pulses, whole grains, nuts, and seeds can help improve mineral bioavailability [38]. Dairy may also play a helpful role: 2 systematic reviews found that consuming dairy products during pregnancy was strongly associated with healthy birth weight and length [39, 40]. Although one review also found a moderately increased risk of large-for-gestational-age babies [40], the overall evidence suggests that the benefits of dairy consumption during pregnancy outweigh the risks.

Second, infants and young children during the complementary feeding period (6–23 mo) have particularly high nutrient requirements and are growing faster than at any other stage in life [30]. They have limited gastric capacity and are at an increased risk of deficiencies of several nutrients that can be more optimally obtained from ASFs, such as EAAs, iron, zinc, and vitamin B12 [41–43]. Even when consuming the estimated total amount of protein recommended, many children in LMICs with insufficient ASF intake have low circulating EAAs, which may indicate inadequate proportions of some of the specific EAAs so as to impair growth and development [42]. Meat intake has been found to reduce the risk of iron deficiency among breastfed infants with low iron intakes and stores [44], and several studies have found that meat, dairy, eggs, and small fish have improved nutrient status and child growth and development in LMICs [45–48]. Furthermore, aquatic ASFs, including fish, mollusks, and crustaceans, have been associated with better child health outcomes and contain nutrients essential for adequate growth and development [49]. Earlier evidence showed equivocal findings for ASFs and young child growth in part because of the heterogeneity in study design and differences in background diet and context [50, 51]. However, evidence from a recent systematic review and meta-analysis of randomized controlled trials in LMICs demonstrates the strong, positive effects of ASFs on child growth [52].

Thus, there is suggestive evidence that ASFs can make a positive contribution to diets during pregnancy and lactation and during infancy and early childhood when there is a high risk of deficiencies in nutrients that are well supplied by ASFs. Two other phases of the life course—adolescence and aging—also merit special nutritional considerations with the need for ASFs.

Adolescence is the life phase with the second-fastest growth velocity, and adolescents simultaneously undergo important reproductive, endocrinal, and neurodevelopmental changes that require nutrient-dense foods [53]. Dairy intake among adolescents has been associated with improved bone health, improved height, and reduced weight and degree of obesity [54, 55], and meat and dairy intake has been shown to improve growth and cognitive outcomes in populations with low intakes, for example, in rural Kenyan school children [45].

Finally, older adults are at increased risk of sarcopenia, frailty, and poor bone health, among other aging effects [56], and may benefit from consumption of ASFs. ASFs contain important nutrients for older populations, including choline, DHA, high-quality protein, and bioactive compounds, such as creatine and carnitine [7]. A systematic review of interventional and observational studies found strong and consistent evidence of the beneficial impact of lean red meat intake on muscle health and protection from sarcopenia [57]. Evidence also suggests that dairy may have beneficial impacts on sarcopenia and frailty [58] and dementia and Alzheimer's [59];however, more rigorous research is needed to confirm these findings. Studies also show associations between at least moderate intakes of ASFs and longevity [60, 61]. However, replacing protein-rich ASFs, particularly processed red meat, with protein-rich PSFs is generally associated with better health outcomes and reduced all-cause mortality [62]. Taken together, the overall evidence suggests that older adults would benefit from limiting processed red meat and consuming ample amounts of protein from both plant and animal sources.

Health Risks

Despite the aforementioned health benefits of ASF consumption, there can be health risks if ASFs are consumed in certain forms or in excess, particularly when not part of a balanced, plant-rich diet. Several compounds found in ASFs have been implicated in NCDs, such as IGF-1, dietary cholesterol, trimethylamine N-oxide, antibiotics, and hormones, which have been reviewed previously [6]. Here, we focus on 3 dietary factors related to ASFs, for which the public health burden is likely most concerning and there are public health guidelines for limiting the NCD risk: processed meat, unprocessed red meat, and saturated fat [2, 3].

Processed meat

Processed meat is inconsistently defined but broadly refers to animal-flesh foods—typically pork or beef but also poultry and fish—that have been preserved through salting, curing, fermentation, smoking, or other processes [2]. Depending on the dose, several compounds found in processed meat likely contribute to various NCDs. These include preservatives, such as sodium, nitrites, and nitrates; saturated fat; and carcinogenic compounds generated from heating meats at high temperatures or smoking, deep frying, or cooking well-done, such as heterocyclic amines, polycyclic aromatic hydrocarbons, and advanced glycation end products [63–67]. High sodium intake, particularly when accompanied by low potassium intake, increases the risk of stroke, cardiovascular disease, and total mortality, especially for hypertensive and older populations; although some evidence suggests that very low sodium intakes may also have harmful health outcomes, reducing excess sodium intakes, for example, by reducing processed meat consumption, which has high sodium levels, is a sound strategy for improving public health [63, 68–72]. Research has associated nitrites and nitrates in processed meats with cardiovascular disease, cancer, and diabetes [73–75]. The World Cancer Research Fund recommends consuming little or no processed meat to reduce the risk of cancer, colorectal cancer in particular, and other NCDs [2]. Although some researchers have challenged the strength of the evidence on the harmful impacts of processed meats [76, 77], others have challenged the methodology of some of this counterevidence [78]. Most evidence suggests that the higher the processed meat intake, the higher the NCD risk on average [79]. Finally, the qualities of different types of processed meats vary widely, which complicates accurate assessment of potentially differential health effects related to different types of processed meats.

Unprocessed red meat

Considering unprocessed red meat, high intakes have been associated with NCDs and mortality, particularly when not consumed as part of a balanced diet rich in minimally processed PSFs [79–87]. In particular, several studies have implicated high intakes of heme iron in cardiovascular disease and diabetes [63, 88–91]. Although there are no upper limits for heme iron in dietary reference intakes, those consuming high amounts of red meat, particularly ruminant meat, would likely benefit from moderating intake and ensuring adequate intakes of fruits, vegetables, whole grains, legumes, nuts, and seeds, which can help protect against NCDs. Additionally, it has been suggested that other compounds in red meat, such as lipid and amino acid metabolites and advanced glycation end products, may play a role in diabetes [63, 92, 93]. Interventional studies generally have not reported that moderate intakes of unprocessed red meat in the context of healthy dietary patterns increase the risk of diabetes markers or other cardiometabolic markers [94–97]. Still, replacing unprocessed and processed red meat with legumes has been shown to improve glycemic parameters in adults [98].

The method of preparation significantly impacts the production of potentially harmful compounds in meat, including advanced glycation end products, heterocyclic amines, and polycyclic aromatic hydrocarbons. Low-temperature cooking methods, such as boiling, poaching, and stewing, produce the lowest amounts, and frying, deep frying, broiling, and barbequing produce the highest amounts [66, 67, 99]. Considering the contribution of unprocessed red meat to nutrient adequacy and other positive outcomes, the recent Global Diet Quality Score suggested that moderate intakes between 9 and 46 g/d make a positive contribution to diet quality, whereas lower and higher intakes do not [100]. The World Cancer Research Fund recommendations to reduce the risk of cancer and other NCDs also recognize the benefits of moderate intakes of no more than 50–71 g/d of unprocessed red meat [2].

Saturated fat

Certain plants contain saturated fats; however, they are more ubiquitous in ASFs, including dairy and meat, particularly red meat. Saturated fats tend to increase apolipoprotein B (apoB) [101], which is an atherogenic protein that increases the risk of cardiovascular disease [102–104]. For this reason, current dietary guidelines recommend limiting the saturated fat intake to <10% of energy [3]. In particular, replacing fats and oils high in saturated fat (e.g., not only animal fats, such as butter and tallow, but also plant fats, such as palm and coconut oil) with unsaturated oils and replacing fatty red meat with pulses, whole grains, fruits, vegetables, nuts, and seeds has been shown to improve the markers of cardiovascular disease [105, 106]. In contrast, replacing saturated fat with refined carbohydrates and sugars provides no benefit to the markers of cardiovascular disease [105, 106].

Considering the overall health effects and public health burden of saturated fat, the evidence is mixed and somewhat controversial. Several systematic reviews and meta-analyses of randomized controlled trials have provided evidence that limiting saturated fat improves serum lipid and lipoprotein concentrations or reduces the risk of cardiovascular disease [107–110]. However, no such studies have demonstrated a significant impact of saturated fat intake on total mortality. Moreover, some researchers have criticized the methodology of some of these studies for having a high risk of publication bias, significant heterogeneity of included studies, and inclusion of studies that were not properly randomized or had inappropriate differences in the diets between treatment and control groups [6, 111]. Several other systematic reviews and meta-analyses of randomized controlled trials and observational studies [112–116], a large observational study of >100, 000 individuals [117, 118], and certain leading health experts [119–121] have not found compelling evidence that saturated fat significantly increases the risk of NCDs or death, on average.

Ultimately, the type of saturated fat, food source, and quantity are important [63, 119, 121], as is the quality of the overall diet [122]. In general, evidence suggests that excess intake of saturated fats that are separated from the food matrix (e.g., butter) is problematic, whereas moderate intake of saturated fats that are contained within complex food matrices, such as yogurt, eggs, and unprocessed meat, and consumed within the context of a healthy plant-rich diet is likely relatively benign [121, 123].

Environmental Risks and Benefits

Similar to the health concerns around ASFs, environmental risks associated with ASF production are a topic of contention among public health and enviornmental sustainability researchers, donors, and policymakers as well as ASF industry stakeholders. Here, we consider both the environmental risks and the benefits of ASFs, focusing on land use, soils, water, biodiversity, climate change, and circularity.

Land use

Livestock uses large areas of land, mostly for grazing and production of feed crops. This land-use conditions the interactions between livestock and the environment and influences most other types of environmental impact. The total global area of agricultural land currently used for livestock production is 2.5 billion ha [124]—~50% of the global agricultural area and ~20% of the total land on Earth [125]. The largest share of this area (2 billion ha) is made up of grasslands (Figure 3). An additional 1.2 billion ha of grasslands are not grazed by livestock and correspond to very marginal rangelands, high altitude or latitude steppes, or shrubby ecosystems [124], which play a vital role as a carbon sink [126]. Of the 2 billion ha of grasslands currently used by livestock, ~0.7 billion ha have an opportunity cost because they could be converted to arable land to produce crops [124, 127]. The remaining 1.3 billion ha of land can be considered nonconvertible because of the steep terrain, marginal soil depth, short growing periods, or other limiting factors. These areas can be used for hunting and foraging; however, the only way to use them for food production is via livestock keeping.

In addition to pastures and rangelands, livestock rely on arable land to produce feed. The total arable land used for livestock feed is ~0.55 billion ha, corresponding to 40% of the global arable land. A large part of this is used for cultivating cereal grains, two thirds of which are eaten by chickens and pigs [125]. In addition, livestock eat coproducts from processing of oilseeds or cereals, such as cakes and straw (accounting for ~0.13 billion ha of land use each). Finally, 0.06 billion ha of land is used to produce silage and fodder beets. All of this land has an opportunity cost in that it could instead be used for food production.

The rise in demand for ASFs in LMICs has resulted in an expansion of the land needed for pastures and feed production in some regions, causing deforestation or land degradation [128]. This change in land use has considerable impacts on soils, water, biodiversity, and climate, which are discussed in detail in the following subsections. It has also led to the competition between feed and food production. However, land use can be optimized by increasing the use of coproducts from processing and residues in animal feed (see the subsection on circularity).

Soils

The majority (95%) of our food is grown from soils. Soils are under continuous anthropogenic pressure, threatening future food security and nutrition [129]. Livestock grazing and feed production can have positive and negative effects on soil health.

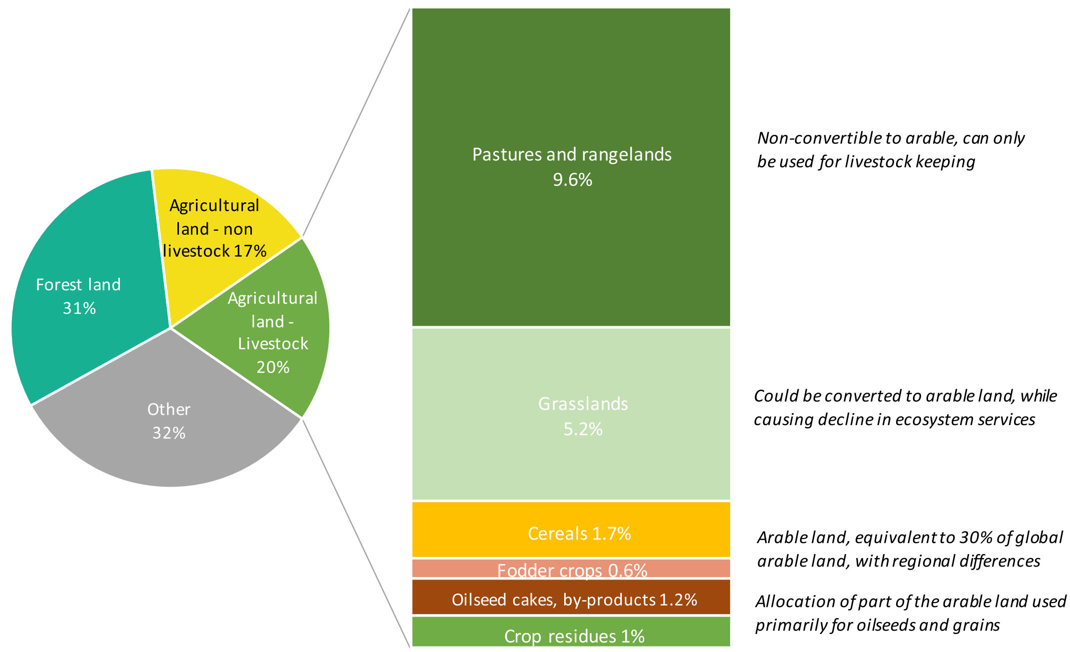

FIGURE 3. Global land use (total 13 billion ha) [125]. Convertible and nonconvertible pastures and grasslands [124]. "Other" includes bare soils, snow, and glaciers.

Livestock manure is used to move organic matter, nutrients, and water within agroecosystems and to increase crop productivity [130–133]. This makes livestock key actors in agroecosystem nutrient cycling and associated ecological and biogeochemical processes [134, 135]. In addition, livestock provides traction for tillage, which also contributes to soil productivity through the incorporation of biomass (e.g., crop residues and manure). It is estimated that draught animals operate on >50% of the planet's cultivated areas [136]. Simultaneously, frequent tillage can also affect soil properties negatively and result in erosion, especially in dry and sandy soils and monoculture systems [137].

Livestock manure is the most commonly available nutrient supply to soils [138], although the nutrients supplied may vary by context [139]. Application of manure can increase the amount of nitrogen and phosphorous available in the soil locally. Although the amount of manure typically applied only provides modest nutrients relative to crop requirements [130, 135], many studies have shown a consistent increase in soil organic matter with manure application [138]. Consequently, manure application slows or limits declines in soil fertility, which is one of the biggest challenges in maintaining healthy soils. Depending on its characteristics and management, manure can also play a critical role in limiting soil compaction and soil temperature regulation [138]. However, excessive amounts of manure lead to nutrient losses via gaseous emissions, leaching, and runoff [140], with subsequent negative effects on the environment. Manure also impacts the presence and availability of trace elements and micronutrients, such as zinc, copper, and manganese [138]. Finally, manure inputs impact the soil's chemical and physical properties, thus affecting the soil organic matter and, subsequently, water retention.

Water

Agriculture currently uses ~70% of the available freshwater supply globally [141], whereas livestock uses ~41% (4387 km^3) of the global agricultural water [141]. Water withdrawal for agriculture (i.e., irrigation and livestock) is expected to increase as global population growth and economic development drive up the demand for food [142]. This is alarming for public health and wellbeing because water scarcity, poor water quality, inadequate sanitation, and droughts already threaten food security, livelihoods, and the health of families across the world [143, 144].

Most water used by livestock represents "green water" (94%) from rainfed conditions [141]. More than one third of green water comes from the production of pastures. Therefore, pasture-based livestock production can be a method to productively use this green water, which would fall on the land with or without livestock. This is particularly relevant for pastures that are located on marginal land, in which case they do not compete with cropland for water.

Consumptive water use varies widely between livestock species. Beef cattle account for 33% of water use compared with that with dairy animals (18%) and pigs (14%). The contribution of livestock's use of water from irrigation (blue water) to the total water use is relatively low: 6% for broilers and 14% for pigs [141]. Livestock water productivity (i.e., the amount of food produced per unit water) is highest for milk, eggs, and pork, with global values between 24 and 26 g of edible crude protein/m^3 of water and 4.9 g of edible crude protein/m^3 of water for beef cattle. These numbers hide substantial heterogeneity between production systems, with ranges varying (e.g., 40-fold for beef and 5-fold for laying hens) depending on feeding practices, level of intensification, productivity, and other factors [141, 145].

The direct and indirect use of water is only one of several water-related challenges that involve livestock. Another critical issue is waste management and disposal of animal feces and urine. Runoff and nutrient leaks from concentrated sources of livestock can be a hazard to the livestock itself, to freshwater sources for humans and wildlife, and to the ocean and marine environments [146–148]. In contrast, livestock systems that are managed within the carrying capacity of the land can favor infiltration and, therefore, regulate water quality and quantity at the landscape level [149–151].

Thus, there is a large and growing water footprint associated with livestock production. Improving water-use efficiency throughout the production system could help improve access to safe water and sanitation and increase the resilience of these systems to external stress, including climate change.

Biodiversity

Livestock contributes directly or indirectly to the 5 main drivers affecting global biodiversity (depicted as green circles in Figure 4). Use of land for pastures and feed crops modifies habitats and, thus, affects biodiversity. The destruction of undisturbed habitats, such as the conversion of the Amazonian rainforest to pastures and feed cropland, has led to substantial biodiversity losses [152]. Land degradation is another form of habitat modification and is a result of inappropriate grazing management (i.e., overgrazing), which can be amplified by climatic extremes [153]. Depending on the regions and agricultural practices, land degradation leads to desertification or woody encroachment, both of which are accompanied by biodiversity losses [153–155].

However, under specific circumstances, habitat modification can benefit biodiversity through the maintenance of seminatural grasslands. For example, in Europe, grassland habitats are among the ecosystem types with the highest biodiversity levels because the long history of livestock farming provided time for a large pool of species to adapt to specific conditions [156]. Adequate grazing management is key to maintaining these habitats and their rich biodiversity [157]. This positive effect on biodiversity has also been identified in other regions (e.g., the United States) [158]. The subtropical and tropical grasslands (savannas) have evolved over millennia, including through their use by pastoralists after the decline of the indigenous megafauna. Thus, appropriately grazed livestock can help maintain the biodiversity of these grassy ecosystems [159, 160]. Conversely, when grasslands are abandoned, they can succeed into shrubland and, ultimately, forests with reduced biodiversity, and this can reduce their resilience, including that to climatic extremes [161, 162].

Livestock also affects biodiversity through the release of excess nutrients into ecosystems, a process known as eutrophication. Such pollution can occur during fertilization of feed crops. For instance, nutrient loading in the Mississippi River due to broad fertilizer use in the central US croplands (mainly used as animal feed) leads to hypoxia and "dead zones" along the river and in the coastal ecosystem [163]. Biodiversity loss through eutrophication can also stem from livestock themselves because of inadequate manure management and disposal at the farm level [164]. At the same time, when used appropriately, livestock manure can play an important role in nutrient recycling and benefit biodiversity [138, 165], as mentioned in the previous section.

Pollution also arises from the use of ecotoxic substances in livestock production. During feed (as well as food crop) cultivation, the excessive use of plant protection compounds, such as pesticides, can have direct negative effects on nontarget species, such as arthropods, and leads to a decline of species at higher trophic levels (e.g., birds) because their food resources become scare. Arthropod species suffering higher mortality due to pesticides include pollinators; their mortality can result in additional losses in agricultural production [155]. These excesses also affect the overall soil fauna, including the soil microbiome [166]. At the animal husbandry stage, pollution by ecotoxic substances can result from the use of veterinary products (e.g., antibiotics, anthelmintics, and hormones). These substances can harm aquatic and soil biodiversity, insects, and scavenger species [167].

Climate change is the fourth driver of biodiversity loss and is detailed in the next subsection.

Pressures on biodiversity can be mitigated, and benefits can be enhanced by following agroecological management practices, which differ across livestock production systems and ecological contexts [168]. For instance, in intensive systems based on external feed supply, the best strategy may be to reduce negative externalities (nutrient losses, greenhouse gas (GHG) emissions, and excessive use of antimicrobials) while increasing the efficiency to achieve high output levels and spare land. At the same time, extensive systems may help maximize benefits to and from biodiversity (e.g., by increasing the biodiversity on agricultural land). Sustainable management practices resulting in higher levels of biodiversity could have additional cobenefits, such as water quality regulation, climate change mitigation and adaptation [169], and enhanced biomass production; these can occur, for example, through agroforestry [170, 171], flower strips [172], and mixed grass-legume areas [173].

The biodiversity of livestock itself is also at risk. Cattle and buffalo breeds represent 25% of the world's 5584 recorded mammalian livestock breeds, and sheep breeds constitute a similar proportion, followed by horses (15%) and goats (11%) [174] and then avian and pig breeds [174]. This very high diversity is the result of hundreds or thousands of years of natural selection and human-controlled breeding, as well as migration and trade in contrasted agroecological conditions where animals adapted, evolved, and developed. Adaptation of breeds to changing environments and demands is a response to the selection of specific characteristics that are needed for the animals to survive and for herders to sustain their livelihoods, such as tolerance to droughts or harsh environments, resistance to diseases, or performance such as yield and body conformation. This diversity is also key to coping with climatic stresses [175].

Thus, livestock has both positive and negative effects on biodiversity and is an important source of biodiversity themselves.

Climate change

Livestock contributes to climate change through GHG emissions and are simultaneously affected by climate change [169]. Thus, they have a role to play in climate change mitigation and adaptation [176]. Agriculture, including livestock, is the third most important sector that contributes to global anthropogenic GHG emissions after energy and industry sectors [176], with estimated emissions from livestock amounting to 8.1 Gt CO_2-eq in 2010 [177]. The largest share of these emissions is from enteric methane, which represents 30% of the global methane emissions.

Overall, the Intergovernmental Panel on Climate Change (IPCC) special report on climate change and land found with high confidence that "supply-side practices can contribute to climate change mitigation by reducing crop and livestock emissions,

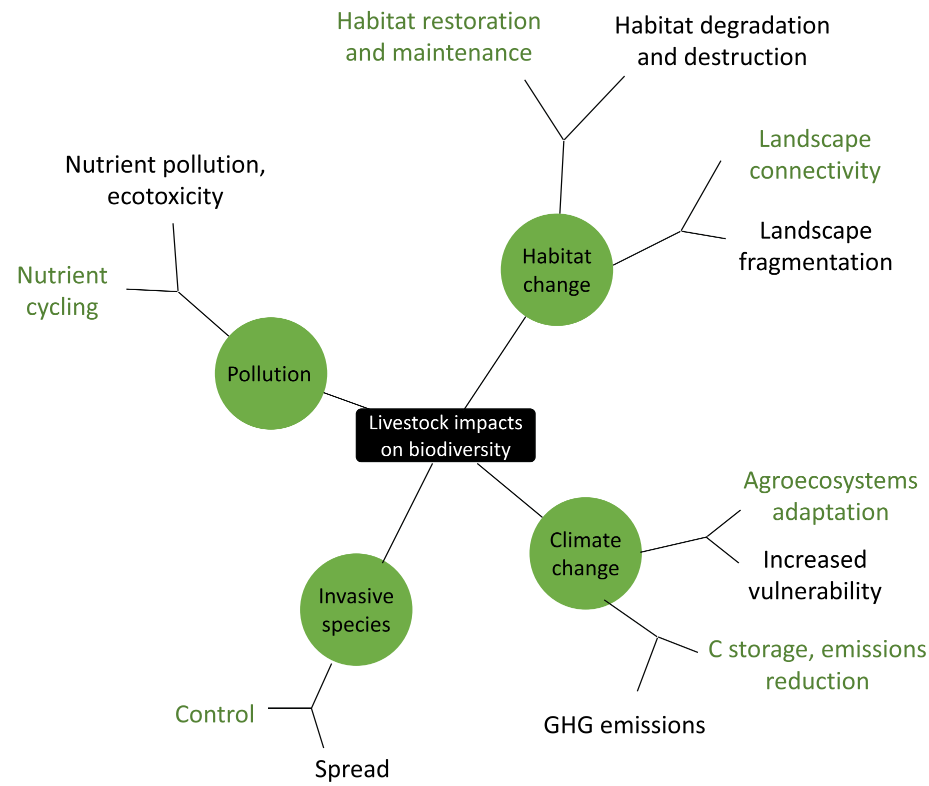

FIGURE 4. Simplified overview of the main impacts of livestock on biodiversity. GHG, greenhouse gas. Adapted from reference 168 with permission.

sequestering carbon in soils and biomass, and by decreasing emission intensity within sustainable production systems" [178, 179]. This importance of livestock in climate change mitigation (as well as adaptation) is well recognized by policymakers: 92 developing countries have included livestock in their nationally determined contributions under the Paris Climate Agreement [180]; however, they may be conditional on access to finance, capacity development, and data [181].

As general guidance, the FAO identified 3 main strategies for climate change mitigation of livestock [182]: (i) improve efficiency and productivity; (ii) better integrate ruminants in the circular bioeconomy [183]; and (iii) increase soil organic carbon content, particularly in pastures. Considering efficiency and productivity, it is estimated that a 14%–41% reduction in GHG emissions from the livestock sector—depending on the production system considered—is possible if all producers adopted the technologies and practices currently used by the most efficient producers [184]. The second strategy involves enhancing the use of coproducts from crop processing and crop residues as feed and recycling energy and nutrients from manure; this is covered in the next subsection on circularity. Considering the third strategy, livestock can contribute to climate change mitigation through improved grazing management. Globally, pastures and rangeland soils are estimated to contain 20% of the global soil carbon (see the previous subsection on soils) [185, 186]. Improved grazing management can increase soil carbon sequestration by adjusting the stocking rate to the carrying capacity [187, 188]. IPCC (2022) estimated the technical potential to reduce emissions through such techniques at 3.5 Gt CO_2-eq/y by 2030 [176]; however, the economic incentives will only permit the achievement of 10%–15% of this potential [179, 188]. The actual achievement of this potential requires not only changes in practices but also long-term policies and an enabling environment for farmers and producers.

Beyond these 3 strategies, there is a further mitigation potential in approaches such as feed supplementation (e.g., lipids and methanogen inhibitors), manure treatment (e.g., acidification), or application (e.g., subsurface injection) [177, 179, 188]. However, such practices are more adapted to production systems in which animals are fed indoors and manures are collected regularly than extensive or low-input systems (those of many small-scale producers worldwide). They also usually come at higher costs than measures targeting efficiency.

In addition to these supply-side measures, demand-side measures have significant mitigation potential [4]. For instance, the IPCC estimates that a shift to balanced, sustainable, and healthy diets, including a reduction of ASF consumption where possible, could lead to a reduction of 1.8 Gt CO_2-eq/y by 2030; in comparison, reducing food loss and waste would lead to a reduction of $<$0.5 Gt CO_2-eq/y [176]. However, the precise scale of reduction that is feasible to achieve is difficult to estimate and varies widely between regions [4]. Researchers often base estimates of the impact of dietary shifts on GHG emissions on emissions per kilogram of products, per kilocalorie, or per kilogram of protein. Only a few studies have considered the nutritional density of foods, especially micronutrients [189], which can result in proposing unbalanced diets to reduce GHG emissions. Despite growing discussion among researchers on including nutrition in food life cycle assessment studies, there is no agreed-upon and established method for defining a nutritional functional unit [189].

In addition to their role in mitigation, livestock is also a tool for climate change adaptation and resilience to climatic extremes. Through their mobility, the possibility of destocking, and their ability to consume diverse feed resources and to mobilize body reserves, livestock can increase the resilience of food production in a changing climate. For example, in the drylands of sub-Saharan Africa, ruminant production has been shown to buffer the impact of climate variability [190]. In addition, animal genetic resources play a key role in adapting to climate change: maintaining a wide variety of species and breeds ensures the availability of greater options should it become necessary to change species or breeds in response to climate change [175].

Circularity

Improving circularity in agroecosystems and food systems involves optimizing the bioeconomy by increasing efficiency, minimizing external inputs and losses, reusing waste, and regenerating ecosystems. Greater circularity is key to enhancing the benefits and reducing the negative impacts of livestock production as it relates to land use, soil health, water quantity and quality, biodiversity, and climate change [127].

Humans harvest ~25% of the total biomass produced on Earth each year [124, 191]. The annual feed intake of livestock represents 20% of this global human appropriation of biomass, or ~6 billion tons of dry matter per year. Livestock consumes one third of the global cereal production as feed (11% of total feed); the rest is mostly composed of plant material that has no or limited other direct food use, such as grass, crop residues, and coproducts from crop processing. The specialized digestive track of ruminants allows them to convert these fibrous plant materials into human-digestible high-quality protein, adding value to the products that might otherwise go unused [124]. The use of such nonfood products as livestock feed can contribute to biomass and nutrient recycling (see the subsection on land use) [124, 192].

Through the use of manure as fertilizer, livestock production recycles nutrients and organic matter (see the subsection on biodiversity). The total nutrients available from livestock manure exceed the nutrients from synthetic fertilizers. Manure could cover >80% of the nitrogen and phosphorus requirements of agricultural plants globally [193] but currently supplies only ~12% of the gross nitrogen input for cropping [130]. This discrepancy is mainly due to challenges regarding the specialization and mechanization of production and limitations of existing subsidies for farm inputs; management constraints and variability in manure nutrient content also play a role [194].

In general, integration of crops and livestock can reduce the need for inputs such as land, water, and nutrients and improve overall efficiency. Better circularity can be achieved by increasing the share of livestock feed that consists of grass, crop residues, and coproducts from processing that humans cannot consume and by recycling and recovering nutrients and energy from animal waste, which includes the application, composting, and anaerobic digestion of manure for biogas production (Figure 5) [195]. Circularity can be achieved at the landscape or supply chain level. For example, large-scale specialized crop and livestock production can link 2 agroecosystems via trade in feed and manure.

Circular livestock systems have the potential to provide a significant share of daily protein requirements (50–60 g) [195]. Nine to 23 g of edible protein per person per day could be supplied from these systems if all types of food waste could be recycled as animal feed. This would also mean a higher share of ruminant meat to harness feeds with low to no opportunity costs. Recent studies have confirmed that circularity could help achieve healthier diets from sustainable food systems in Europe if diets were also adjusted to nutritional requirements, therefore avoiding inadequate or excess consumption [196, 197].

Reducing waste can also happen during transport and processing of animal products. For example, organ meats (offal) are nutrient-dense foods that make up 10%–15% of the liveweight of an animal but are not always consumed [198]. Processing and consuming more organ meat can contribute to reducing waste and enhancing the use of animals, thereby reducing further environmental impact. For example, allocating GHG emissions to part of the byproducts of a carcass in the French meat industry could reduce the carbon footprint of meat by 6% [199].

Several actions are needed to foster an enabling environment for greater circularity in ASF production. There remains a need to assess the amount of biomass that can be potentially recycled as livestock feed and the impact this recycling would have on productivity. Research and regulation also need to address externalities and existing subsidies on inputs (e.g., fossil fuels or fertilizers), difficulties in adapting technical solutions to location-specific conditions, and the lack of access to knowledge and technologies. Regulatory frameworks that consider the technical requirements for better integration of nonedible products into livestock feed and potential health trade-offs can support circularity. For example, in Japan, 80% and 57% of the business food waste that was obtained from food manufacturing and wholesaling, respectively, generated in 2017 were recycled into animal feed and fertilizer, thanks to adequate policies, including a certification system and mandatory heat treatment to avoid disease risks [200, 201].

Figure 6 proposes a summary of the main positive and negative interactions between livestock and the environment and illustrates how circularity can help enhance the positive impacts.

Alternative Proteins and Protein-rich Foods

Alternative proteins refer to protein-rich foods produced from nonanimal sources. They include proteins or protein-rich foods made from plants, fungi, cells, algae, and insects. Although many of these foods are not widely available, particularly in LMICs, researchers, policymakers, and entrepreneurs expect them to play an increasing role in the future. In this section, we consider each main type of alternative protein in turn, discussing the existing evidence on its nutritional and environmental impact.

Plant-based alternatives are currently the most widely accepted alternative protein-rich foods [202]. They typically consist of minimally processed pulses (e.g., tofu and soy milk) or ultra-processed foods that include plant protein isolates (e.g., plant-based burgers). Considering the environmental impacts, life-cycle analyses from Beyond Meat and Impossible Foods suggest that their plant-based beef products have lower environmental impacts than those of conventionally produced beef and similar impacts to those of conventionally produced pork and chicken, with the highest impacts coming from energy and GHG emissions and lowest impacts coming from land use and eutrophication [203].

From a nutrition standpoint, some plant-based alternatives can provide similar nutritional value to ASF counterparts in terms of what is listed on "nutrition facts" panels; however, when

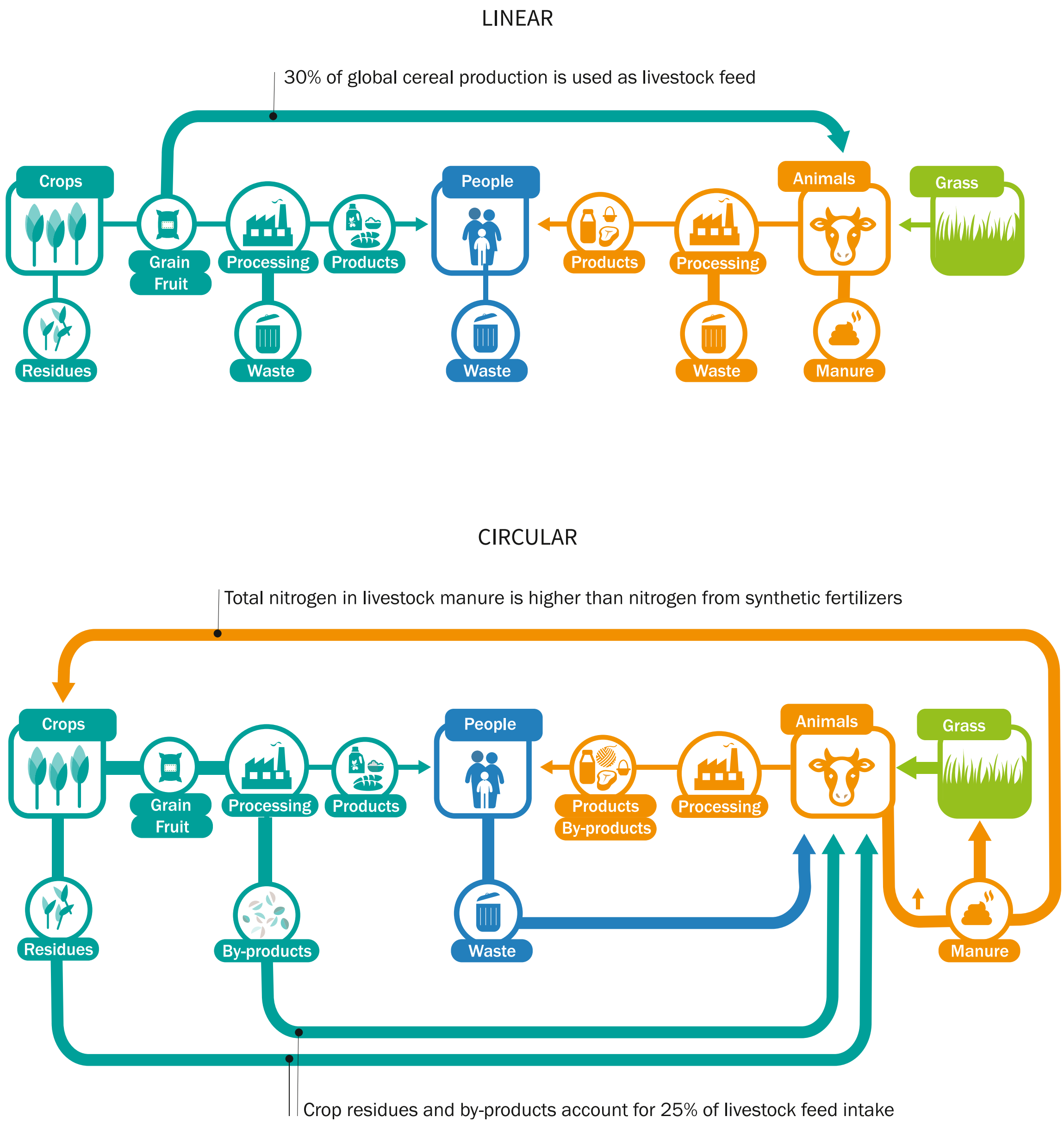

FIGURE 5. The role of livestock in the bioeconomy, currently between linear and circular. Reproduced from reference [223] with permission.

compared using metabolomics, they differ substantially [204, 205]. The health implications of these differences are poorly understood; however, there may be some benefits of plant alternatives (e.g., more fiber, potassium, folate, magnesium, and phytonutrients) and some trade-offs (e.g., more sodium content and ultraprocessing; lower-quality protein; and less calcium, vitamin D, and beneficial compounds unique to ASFs, such as creatine and anserine) [205–207]. One randomized crossover trial suggests that there may be cardiovascular benefits with plant-based meats compared with animal-based meats [206]. Another randomized clinical trial suggests that there may be increased risk to bone health from plant-based alternatives compared with ASFs [207]. In general, plant-based soy foods, such as soy milk and tofu, tend to have similar protein quality to that of ASFs; however, other plant-based foods have lower protein quality (Figure 1). This may have little relevance in high-income contexts with adequate protein intake and dietary diversity; however, it can be important in contexts where diets are marginal [28]. Plant-based milks other than soy milk may not be suitable nutritional replacements for cow milk, particularly in LMICs, given their much lower protein content and quality and lower micronutrient density [208]. Adequate fortification of plant-based milks can help improve their micronutrient density but does not address the lower protein content unless protein isolates are also added. Given that two thirds of the global population have lactose malabsorption [209], plant-based milks are an important replacement for cow milk; however, their nutritional composition and any differential health impacts need to be assessed.

Fungal protein (also called mycoprotein) is a high-quality protein-rich food produced by fermentation. Mycoprotein is rich in protein and fiber; can be rich in zinc, magnesium, calcium, and vitamin B12; and has been associated with reduced blood cholesterol concentrations and short-term energy intake [210]. Life-cycle analyses are limited but suggest that mycoprotein has a lower environmental impact than beef and a similar impact as chicken and pork, the highest impacts coming from

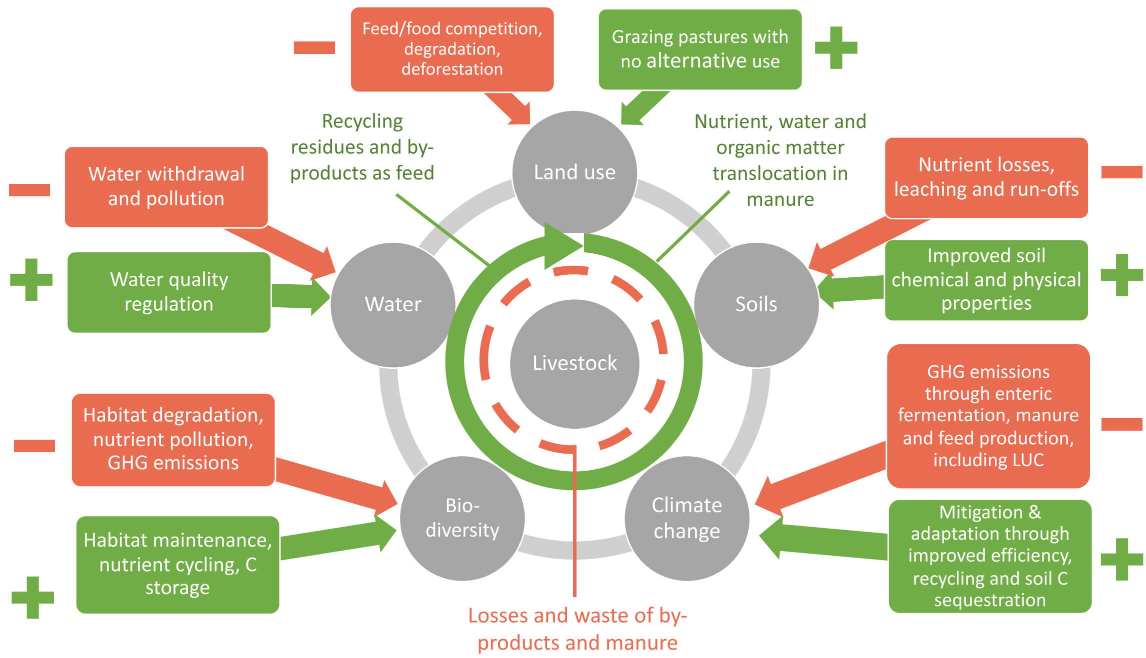

FIGURE 6. Summary of the main positive and negative interactions between livestock and the environment. C, carbon; GHG, greenhouse gas, LUC, land-use change.

energy and emissions, with negligible impacts from eutrophication and land use [203, 211].

Cell-based (also called laboratory-grown, in vitro, and cultured) meat uses cultured cells to produce meat [203]. The evidence base of the nutritional and environmental impacts of cell-based meat is limited; however, some researchers anticipate potential improvements in both types of impacts over livestock-based meat [203]. Scaling up of the production of cell-based meat is currently limited by high production costs, knowledge gaps, and low consumer acceptance [203]. Precision fermentation, which ferments genetically engineered microorganisms, can also be used to sustainably produce ASF protein ingredients, such as whey and gelatin [212].

Algae-based protein-rich foods are rich in high-quality protein, essential fatty acids, micronutrients, and beneficial bioactives and have potential to be sustainably produced [213]. However, the high cost of harvest and extraction and limited public awareness have hindered the development of algae-based foods other than as supplements or secondary ingredients [213].

Insect-based proteins, such as beetles and caterpillars, among others, are rich in high-quality protein, fiber, vitamin B12, iron, zinc, EAAs, and antioxidants and can be produced sustainably [214]. Although nearly 2 billion people consume insects worldwide, consumer acceptance is still a key barrier to increased intake, particularly in high-income countries [214].

Although manufacturers of alternative proteins and protein-rich foods and their advocates often promote them as being nutritionally interchangeable with ASFs, some nutrition experts have cautioned that using the term "protein" to describe a heterogenous set of foods fails to recognize the unique nutrients and benefits of different protein-rich foods and their role in cultural traditions [215]. Moreover, beyond overemphasizing protein, private-sector–led efforts toward a "protein transition" may increase power imbalances through concentrated corporate-led solutions using monocultures and ultraprocessing that may not lead to the intended benefits to human and environmental health [216–218]. Nevertheless, alternative proteins and protein-rich foods show increasing potential for benefiting human and environmental health when produced appropriately, with careful attention to food quality and safety, cultural traditions, and sustainable agroecological principles [216, 219].

Conclusion

ASFs are a diverse group of foods that have unique properties and can contribute to healthy diets in important ways. ASFs are rich in bioavailable nutrients that are commonly lacking globally, including iron, zinc, calcium, vitamins B12 and D, choline, EPA, DHA, and EAAs. ASFs and PSFs have complimentary nutrient profiles, and diets containing both ASFs and PSFs reduce the risk of nutrient deficiencies. At the same time, excess consumption of processed meat, red meat, and saturated fat can increase the NCD risk. ASF production generally has a large environmental impact; yet, when produced at an appropriate scale and in accordance with local ecosystems and contexts, livestock can play an important role in circular and diverse agroecosystems that, in certain circumstances, can help restore biodiversity and degraded land, mitigate GHG emissions from food production, and contribute to food security and nutrition for populations worldwide.

There is no one-size-fits-all approach or overall amount of ASF that is healthy and environmentally sustainable. It depends on the local context and health priorities and will inevitably change over time as populations develop; as nutritional concerns evolve; and as alternative foods from new technologies become viable, sustainable, affordable, and accessible. Populations consuming high levels of meat, particularly processed meat, would generally benefit from reduced consumption (with dividends for both human and environmental health). In contrast, those who consume low levels of ASFs and at a risk of undernutrition would generally benefit from increased consumption. Any efforts by policymakers, donors, international organizations, or civil society groups to increase or decrease ASF consumption should be considered in light of the nutritional and environmental needs and risks in the local context and, importantly, integrally involve the local stakeholders impacted by any changes.

All ASFs have a role to play in certain contexts to optimize the use of the various ecological conditions and accommodate diverse cultural traditions across the globe. For example, ruminant livestock and dairy have the potential to be sustainably produced where rangelands make up a large portion of the available land, whereas aquatic ASFs could be prioritized in areas with access to large bodies of fresh or salt water. At the individual level, healthy and sustainable diets can take many forms, ranging from plant-exclusive diets to those rich in a diversity of ASFs and PSFs. There is no one-size-fits-all role of ASFs applicable across contexts, and their role will inevitably evolve over time. However, ASFs, including meat, dairy, eggs, and aquatic ASFs, do play important and distinct roles in achieving healthy and sustainable food systems in different contexts worldwide and will continue to do so for the foreseeable future. Efforts are needed to ensure best practices of production, curb excess consumption where high, and sustainably increase consumption where low.

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SECONDARY ABSTRACT

Scientific and political conversations about the role of animal-source foods (ASFs) in healthy and sustainable diets are often polarizing. To bring clarity to this important topic, we critically reviewed the evidence on the health and environmental benefits and risks of ASFs, focusing on primary trade-offs and tensions, and summarized the evidence on alternative proteins. ASFs are rich in nutrients commonly lacking globally and can make important contributions to healthy diets. Many populations in Sub-Saharan Africa and South Asia could benefit from increased consumption of ASFs. Where consumption is high, processed meat should be limited, and red meat and saturated fat should be moderated to lower the risk of chronic diseases—this could also have cobenefits for sustainability. The amount and type of ASF that is healthy and sustainable will depend on the local context and health priorities and will change over time. Efforts by governments and nongovernmental organizations to increase or decrease ASF consumption should be considered in light of the health and environmental needs and risks in the local context and involve the people impacted by any changes. Policies, programs, and incentives are needed to ensure best practices in production, curb excess consumption where high, and sustainably increase consumption where low.

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