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REVIEW

Carbon tunnel vision and sustainable meat production in the West: A disproportionate focus on dietary greenhouse gas emissions?

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Abstract

Livestock systems represent a considerable environmental challenge. In response, various scientists, non-governmental organisations, and policy makers claim that Western populations in particular need to sharply reduce meat consumption. Given people's attachment to meat, many of these actors favour hard policy interventions based on a range of systemic financial and legal reforms that would go beyond mere nudging and the formulation of recommendations, including the top-down imposition of meat taxes and bans, as well as herd size reductions, which would lead to sharply higher prices. However, arguments in support of such policies tend to oversimplify the issue, ignoring regional variations, mitigation potential, and broader ecological and nutritional contexts. The focus of this article is on dietary greenhouse gas (GHG) emissions as a main target for environmental policymaking, with all livestock production in the West contributing 2.6% of total anthropogenic GHG emissions globally. From a consumption perspective, reductions in meat eating represent a saving of 1–6% on the total individual carbon (C) footprint of an average Westerner, depending on dietary restrictiveness. However, such estimates need to account for differences in nutritional value when comparing animal and plant-based foods, as well as to factor in co-product benefits, C sequestration in grazing systems, natural baselines in rewilding scenarios, constraints on afforestation, the potential risk of "carbon leakage", and distinct evaluation metrics for biogenic (enteric) methane *versus* fossil-fuel derived carbon dioxide. Carbon tunnel vision, hyperbolic narratives, and misguided policies risk compromising pathways to reasonable reform of existing meat industries, which are desirable and urgent.

Keywords Sustainable food systems · Dietary policy · Carbon sequestration · Life cycle assessment · GWP* · Biogenic methane

Introduction

The global food system constitutes a substantial environmental burden, exerting influence on carbon (C) budgets, water resource depletion, soil and freshwater quality, biogeochemical nutrient cycling, patterns of land use, and biological diversity. The extent of its contribution to human-induced greenhouse gas (GHG) emissions is uncertain but has been situated between 1/5 and 1/3 of the total (Vermeulen et al., 2012; Crippa et al., 2021). Within this system, agriculture and fisheries directly contribute about 40%, while land use and land-use change (LULUC) and supply chains each generate about 30%.

Because animal-sourced foods, in particular those obtained from methane-generating ruminants, tend to have higher C footprints per unit of mass or per calorie than foods from plants, so-called "plant-based" diets are advocated to meet climate targets (Poore & Nemecek, 2018). Some of the more zealous proponents advocate for a transition towards diets that are either vegan, vegetarian, or very low in animal-sourced foods. They are calling for hard policy interventions to restrict dietary choice, thereby mobilizing a range of economic and financial options, such as taxes or even bans on meat and dairy (for a detailed discussion, see Leroy et al., 2023). These policies are often technocratic in nature, largely designed by vocal and influential Western

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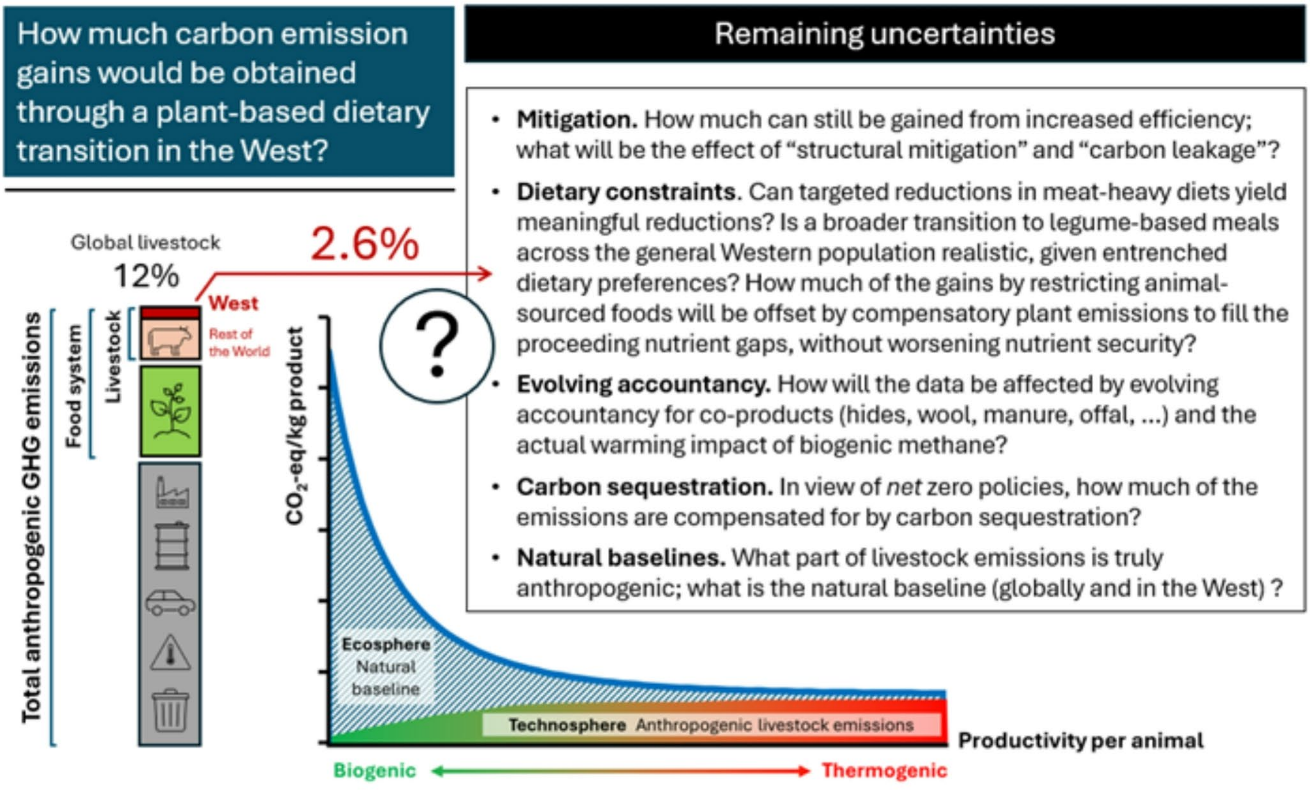

How much carbon emission gains would be obtained through a plant-based dietary transition in the West?

Remaining uncertainties

- **Mitigation.** How much can still be gained from increased efficiency; what will be the effect of "structural mitigation" and "carbon leakage"?
- **Dietary constraints.** Can targeted reductions in meat-heavy diets yield meaningful reductions? Is a broader transition to legume-based meals across the general Western population realistic, given entrenched dietary preferences? How much of the gains by restricting animal-sourced foods will be offset by compensatory plant emissions to fill the proceeding nutrient gaps, without worsening nutrient security?
- **Evolving accountancy.** How will the data be affected by evolving accountancy for co-products (hides, wool, manure, offal, ...) and the actual warming impact of biogenic methane?
- **Carbon sequestration.** In view of *net* zero policies, how much of the emissions are compensated for by carbon sequestration?
- **Natural baselines.** What part of livestock emissions is truly anthropogenic; what is the natural baseline (globally and in the West) ?

Fig. 1 Contribution of livestock to total anthropogenic greenhouse gas (GHG) emissions, globally (12%) and in the West (2.6%), as estimated by GLEAM 3.0 (FAO, 2026), and an overview of contextualizing factors (the natural baseline graph is modified after Manzano et al., 2026, with pastoralism at the left side of the spectrum and the most industrialized systems at the right, showing how much of the emissions in global low-productivity systems are natural and inevitable, and should not be counted as anthropogenic; for a detailed discussion, see Sect. Ecological considerations: natural baseline emissions and afforestation)

intellectual elites in privileged positions (Ederer, 2024; Leroy et al., 2025a, 2025b). However, such self-proclaimed food system experts overlook real-world complexities in low- and middle-income countries, while making unreasonable demands related to meat production and consumption in Western countries (hereafter referred to as "the West", consisting of Europe, Northern America, Australia, and New Zealand). The assumption that Western citizens must radically reduce meat intake to allow for its consumption by the world's poorest is not only dependent on naïve redistribution economics and counterproductive central planning schemes, it is also insensitive to a range of ecological, nutritional, and societal implications that risk creating harmful outcomes on landscapes and foodscapes (Leroy et al. 2025a).

This review examines arguments for nuance, with a focus on the topic of GHG emissions, as these are at the heart of the debate on sustainable livestock transitions in the West, potentially leading to an underestimation of complexities through carbon tunnel vision and, therefore, unintended consequences (Fig. 1).

Regionality of livestock emissions and their mitigation potential

Global aggregates mask regional differences

Exaggerated estimates of livestock's impact on global C budgets circulate on social media and beyond, including a claim that > 50% of all GHGs are produced by animal agriculture (Boucher, 2016). Currently, the most authoritative estimate is that livestock accounts for approximately 12% of the total, with slightly more than half due to direct emissions (FAO, 2026; seafood and fisheries provide another 1% of animal-food related emissions). Yet, this global estimate comes with its own limitations and context, as it masks regional heterogeneity. Livestock production in the West generates 2.6% of global GHG emissions, whereas Africa, Central/South America, and Asia contribute 1.3%, 3.1%, and 5.2%, respectively. When using the more formal World bank classification of "high-income countries" instead, the contribution to global GHG emissions is equally estimated at 2.6%. For the EU27 alone, this amounts to 1.0% of total GHG emissions (for comparison, BRICS countries contribute 5.3%), with 0.7% from ruminants and 0.3% from monogastrics (FAO, 2026). Only part of that pertains to meat, the rest being ascribed to dairy, poultry, and eggs.

This variability across regions not only depends on herd size differences, but also on variations in production efficiency and emission intensities. For beef, average emissions intensities are 12–16 kg of CO_2 equivalents (CO_2e) per kg of carcass weight for Europe and Northern American countries, 53 kg/kg in Latin American and Southern Asian countries, and 72 kg/kg in Sub-Saharan African countries (FAO, 2026). These differences are due to discrepancies in feed quality, genetics, management, and socio-cultural roles, with a different focus on wealth, draft power, fuel, and religious significance (Thompson & Rowntree, 2020). Europe is at the lower end of the spectrum, as most beef comes from dairy animals (calves count as by-product of milk production, whereas cull dairy cows have a lower footprint compared to beef breeds due to a life-long impact being allocated to milk and, usually, the fact that they are more intensively raised). In addition, due to the complexity of collecting accurate data associated with C removals on farm, average emission data are usually reported as gross and not net emissions. This is particularly important within livestock systems which focus on grasslands, as for ruminant-based grazing operations (cf., Section "Carbon sequestration and pathways to net zero emissions").

Mitigation potential

In addition to being respectful of local contexts, future-oriented policies should consider that GHG emissions are not static but are evolving based on changes in economy, trade, and technological advancements. According to the roadmap established by the United Nations' Food and Agricultural Organization (FAO, 2023a, 2023b), GHG emissions of livestock systems can be reduced while meeting rising demand through efficiency gains and C removals. By doing so, livestock agrifood GHG neutrality can in principle be achieved by 2050, even if this requires the setting of ambitious targets, including a 25% methane (CH_4) reduction by 2030 and an annual productivity growth of 1.7% until mid-century. Options to advance C footprint reduction are multiple and include improvements in feed strategies, genetic improvement, veterinary care, smart use of manure, the valorisation of biogas, better rotation schemes, grazing and herd management, enhanced integration with crop agriculture, soil pH and organic matter improvement, renewable energy use, reusing meat-processing by-products, increasing the consumption of edible offal, and waste reduction (European Commission, 2020; Pulina et al., 2020; Thompson & Rowntree, 2020; Kyriazakis et al., 2024). For beef specifically, shortening the production cycle, improving feed efficiency, integrating beef and dairy systems, and increasing the use of non-edible feed resources have been identified as key levers to reduce impact per unit of edible output (Pulina et al., 2021).

Carbon footprint reduction strategies on farm thus fall into four focused areas, involving: (1) the animals – focus on performance via genetics, health, and methane-reducing feed supplements; (2) inputs – focus on embedded C via feed, fertilizer, fuel, medication, etc.; (3) land – focus on C capture via soil health, plant biomass, etc.; and (4) green energy – focus on reducing fossil fuel use via manure valorization, solar, wind, etc. These four areas will have to be applied at different extents dependent on the livestock enterprise, to both lower emissions and improve C capture, at both sides of the equation. Of course, different GHG gases (carbon dioxide: CO_2, CH_4, and nitrous oxide: N_2O) will be targeted across different interventions, and it is important to recognize the difference between biogenic and thermogenic (fossil-fuel) derived emissions, as achieving zero emissions from agriculture is not possible, nor the aim (which is to balance C emissions with capture).

Margins for efficiency improvement are the largest in some regions of Sub-Saharan Africa and South Asia, where production growth is also still driven by increases in animal numbers, and much less so in the West even if at least some potential is still present (Gonzalez Fischer & Herrero, 2026). For example, further improvements in the pork chain have been obtained through better genetics, management, and long-term production efficiency gains in both Norway (Bonesmo & Gjerlaug Enger, 2021) and Australia (Wiedemann et al., 2024). Paralleling animal performance gains, the enteric emission from German meat and milk production are now lower than in the mid-1980s, even approaching levels reached during the late 19th century (Kuhla & Viereck, 2022). In the US, industry-wide reviews highlight that improvements in production efficiency have historically driven reductions in emissions intensity per unit of product in dairy systems (Peterson & Mitloehner, 2021). In improved grassland systems, transition towards more multi-functional swards, particularly those containing nitrogen-fixing legumes, have potential to not only reduce CO_2 emissions associated with inorganic fertilizer production but also to reduce N_2O emissions. This reduction is associated with lower nitrogen (N) application to swards and improved soil health, reducing N_2O formation (McAuliffe et al. 2020a).

Feasibility and implications

Even if, from a production-system perspective, sustainability can be driven by substantial improvements in productivity, efficiency, and system integration, rather than by output reduction or by necessarily compromising meat production (Gonzalez Fischer & Herrero, 2026), some words of caution are required. Missing mitigation targets, including the ones outlined in the FAO Pathways document (FAO, 2023a, 2023b), would not merely delay progress but also risk rendering the net-zero livestock pathway unattainable without far more disruptive interventions. For instance, a failure of supply-side assumptions would likely necessitate to be compensated by larger consumption reductions, especially in high-income countries, thereby risking economic disruption and equity issues if not managed justly. Neglect and over-optimism could thus lead to locked-in higher emissions and costlier course corrections at later stages.

To further complicate matters, the feasibility of future mitigation strategies at the production level will depend on the access of farmers to services and resources, and their overall willingness to contribute in the light of severe economic challenges and uncertainties. A central question in this regard remains who ultimately bears the costs, and whether farmers and ranchers are adequately rewarded or monetized for emissions avoidance (e.g., through incentive-based policies and carbon credits).

Moreover, reduction of livestock herds in Western countries due to policies aimed at cutting domestic emissions may lead to "carbon leakage", which would then simply displace production to regions with higher emission intensities, resulting in little to no net decrease, or even an increase, in global GHG emissions (Adenaeuer et al., 2023; Merlo et al., 2026). However, for a fair evaluation, it is important to as well bear in mind that the low GHG emission intensities in industrial countries are likely to not have been exclusively achieved by improvements in herd or sward management, but also through cattle feed replacement that approaches that of monogastric animals, resulting in an actual increase of fossil-fuel based, technosphere emissions (Manzano et al., 2025).

Conversely, so-called "structural mitigation", based on international trade to relocate meat production towards areas with the lowest emission intensities, such as the West, could negatively compromise local livelihoods and other societal benefits of livestock in regions of the Global South, while increasing the burden of harmful nutrient accumulation in regions with high animal densities (Gonzalez Fischer & Herrero, 2026). Furthermore, reducing grazing pressure in extensive systems may lead to unfavorable ecological effects, for instance affecting biodiversity and increasing the risk of wildfires (Anadón & Sala, 2026).

Putting the carbon gains of "plant-based" diets into perspective

Compensatory effects of "plant-based" shifts

To meet climate targets, too much is often expected from transitioning towards diets that are low in animal products. Globally, net dietary shifts per guidelines are estimated to contribute only 4% to the required mid-century mitigation effort for livestock, which reflects a reduction in consumption in the West that is partly offset by a required increase in the global south, particularly in Africa (FAO, 2023a). Moreover, eliminating livestock does not proportionally reduce emissions due to dietary substitution effects, because removing animal-sourced foods often requires a higher production of plant foods to fill proceeding nutrient gaps, which will then generate its own emissions. In some cases, this can even result in severe soil C losses and increased N_2O emissions from agricultural soils, as has been suggested for a shift towards the EAT-Lancet diet in a Danish context (Michailidis et al., 2025). In addition to affecting emissions from soil, the conversion of grasslands to arable cultivation may also cause nutrient loss into water courses (Blackwell et al., 2024).

Establishing a vegan food system in the West would therefore not be as simple as merely cutting out livestock's 2.6% contribution to global anthropogenic GHG emissions, but also requires factoring in compensatory land-use changes, loss of nutrient cycling via manure (resulting in increased synthetic fertilizer requirements), and increased crop production and transportation to fill nutrient gaps, resulting in limited net benefits.

Order of magnitude of carbon savings

Modelling has indicated that the complete removal of livestock in the US would cut total national emissions with <3%, while risking nutrient inadequacies (White & Hall, 2017). Therefore, shifts to flexitarian, vegetarian, and vegan diets need to be assessed based on actual dietary patterns, saving 0.2, 0.5, or 0.8 t CO_2e, respectively, on a Western annual *dietary* footprint of 1.5-2.0 t CO_2e/person (Leroy et al., 2022). Importantly, this reduction may appear as substantial within a *dietary* C budget but leads to a minor difference when contextualized within the *total* annual C footprints of most Western individuals (9–15 t CO_2e/person; with Europe and North America being at the lower and higher ends, respectively). In contrast to what is often assumed, diet is therefore not the dominant climate lever in the West. Carbon-intensive footprints in the West are mostly shaped by housing, transport habits and tourism, consumer goods and fashion, and - increasingly - digital infrastructure and data centres (Andrae & Edler, 2015; Wynes & Nicholas, 2017; Belkhir & Elmeligi, 2018; Lenzen et al., 2018; UNFCCC, 2018). Overstating effects from dietary choices risks distracting from the more impactful emissions related to the reliance on fossil fuels (Haniotis, 2019). For instance, living car-free yields annual savings of 1.0–5.3 t CO_2e per person, while a single round-trip long-haul flight generates 0.7–2.8 t CO_2e per person (Wynes & Nicholas, 2017), thereby offsetting years of dietary mitigation based on the restriction of meat.

Based on the above, the eventual C saving for a meat-reducing Westerner would be limited to a few percentages only, in the order of 1–6% on total C footprint estimates (depending on dietary restrictiveness, with flexitarian-style meat reduction being at the lower end; Leroy et al., 2022). For New Zealand, reductions in consumption-based emissions have been estimated at a mere 2–4% for meat-substituted diets, calculated on a lifetime basis (Barnsley et al., 2021).

Duration and acceptability of "plant-based" shifts

The duration of the diet is of major importance, because gains are only meaningful when sustained over longer periods, which becomes more unlikely with higher degrees of dietary restrictiveness. Indeed, most individuals adopting vegetarian/vegan diets in the US revert to including animal-sourced foods, with more than half of them abandoning the diet within a year (Asher et al., 2014). Moreover, massive economic and cultural intervention efforts would be needed to enable a radical shift from animal-sourced foods to pulses, which currently provide only a small minority of bioavailable protein in the West. This would need to unrealistically overrule dietary preferences and eating habits, with potential implications for digestive comfort and overall nutrient status.

Nutritional value and co-products should be accounted for

The importance of nutritional adequacy

Besides having only a modest impact on total C footprint reductions, adopting diets low in meat and other animal-sourced foods may come at the cost of nutritional adequacy, worsening intakes or status of several priority micronutrients (Payne et al., 2016; Beal et al., 2023; Leonard & Kiely, 2024; Leonard et al., 2024; Fedde et al., 2025). A recent large-scale intervention trial demonstrated greater inadequacies in B-vitamins (B2, B6, B12), iodine, calcium, zinc, and selenium among participants assigned to the low-emission diet arm compared to controls, who consumed more dairy, meat, and eggs alongside fewer legumes, nuts, and seeds (Leonard et al., 2025). Particular attention is warranted for at-risk groups, such as pre-menopausal and, especially, pregnant and lactating females, for whom plant-based transitions may worsen already problematic iron deficiency levels (Hallström et al., 2025). In a Finnish context, a one-third reduction in dietary C footprints was evaluated by the authors as nutritionally feasible, but more aggressive shifts raised nutritional concerns, particularly regarding iron adequacy in female populations (Irz et al., 2024). Without supplementation, vegan diets may also fail to provide adequate levels of selenium, as plant-based foods are more variable in selenium status reflective of soil conditions in which they are grown, whereas animal-sourced foods are more consistent due to metabolic regulation and dietary supplementation to meet animal requirements (Kao et al., 2025).

Studies have shown that typically a minimum of half of all protein intake should be from animal sources to facilitate the achievement of an adequate intake of all micronutrients (Vieux et al., 2022; Ridoutt et al., 2025), or, alternatively, about one-fourth to one-third of the caloric intake (Leroy et al. 2025b). Furthermore, diets containing a variety of protein sources are more likely to achieve recommended nutrient intakes (Ridoutt et al. 2022b). In Australia, diets containing more red meat were also associated with higher vegetable intake, which is relevant because many Western diets fall far below the recommended intake of vegetables (Ridoutt et al. 2022a). Therefore, taking a total diet approach is most important. Conceptual dietary recommendations that do not align with customary meal and food combinations are unlikely to achieve much adoption.

Within the broader sustainability framework of people, planet, and prosperity, nutritional inadequacy represents its own sustainability failure. Sustainability metrics should not overlook that livestock production offers substantial and multiple nutritional contributions to global food baskets (de Lange et al., 2025). Recent methodological developments in nutritional life cycle assessment (nLCA) have attempted to move beyond mass-, calorie, or protein-based functional units by explicitly incorporating nutrient quality and density into environmental metrics. Early contributions highlighted the sensitivity of climate impact rankings to the choice of nutritional functional unit (Sonesson et al., 2019). Subsequent work formalised protein quality as a complementary functional unit, which can substantially alter GHG emission intensities expressed per unit of protein, although primarily as a sensitivity analysis given the limitations of current data (McAuliffe et al. 2023a). In Ireland, climate policies promoting beef replacement with plant-based proteins may increase total net protein output, but a decrease in net digestible protein and essential amino acids is likely due to lower protein quality and digestibility of plant proteins compared to beef (Merlo et al., 2026). More recently, product-group-specific nutrient indices have been proposed and applied directly as functional units in cradle-to-plate nLCAs of protein-rich foods, integrating protein together with key micronutrients and adding further nuance to the topic when multi-nutrient indices are adopted (Kyttä et al., 2023; Tukiainen et al., 2025). One approach specifically focuses on the comparison of production-systems for livestock in terms of nutritional quality functional units (De Lange et al., 2025). Despite these advances, the application of nutrient-based functional units remains limited, heterogeneous, and rarely used to enable quantitative comparison or synthesis of GHG emissions from animal-sourced foods across studies.

Limitations of alternative proteins

To overcome the nutritional discrepancies caused by the restriction of animal-sourced foods, "alternative proteins" are promoted as low-emission substitutes for conventional protein sources from livestock. Although this represents potential environmental benefits and a potentially lucrative market innovation option for global agrifood corporations and vegan-tech startups (Leroy et al., 2023), these products historically failed to convince or interest most consumers. Moreover, a closer examination reveals challenges related to: (1) environmental impact, (2) nutrient value, and (3) public health, among other issues (Chriki et al., 2025).

Firstly, GHG footprints are not uniformly superior. Plant-based alternatives (e.g., mock meats) exhibit footprints ranging from 1 to 7 kg CO_2e per kg, lower than those of ruminant meats (10–130 kg CO_2e per kg of food globally, excluding the higher extremes of "deforestation" beef, or about 10–60 CO_2e per kg of food in the West, depending on the production system), but often comparable to poultry or eggs (2–7 kg/kg) and pork (3–11 kg/kg) (de Vries & de Boer, 2010; Nijdam et al., 2012; Apostolidis & McLeay, 2016; Souza Filho et al., 2019; Bonesmo & Gjerlaug Enger, 2021; Pingali et al., 2023). Moreover, LCAs frequently underestimate impacts arising from energy-intensive processing steps (Aimutis & Shirwaiker, 2024). Environmental profiles of cultivated (lab-grown) meat are particularly uncertain and variable, being highly sensitive to assumed energy systems. Carbon footprints of 7 kg CO_2e per kg (3–25 kg/kg) have been calculated, exceeding those of most pork or poultry while offering no clear advantage over beef when using specific warming potential metrics (Mattick et al., 2015; Lynch & Pierrehumbert, 2019; see also Sect. "Biogenic CH_4 and atmospheric complexities"). When growth media and high-purity chemicals are accounted for, the estimates were even 4-25x higher than for median conventional beef (Risner et al., 2025).

Secondly, the substitution potential is usually evaluated solely on the basis of caloric and protein content, overlooking the broader nutrient profile of animal-sourced foods, which should not be taken lightly (as mentioned above, Section "The importance of nutritional adequacy"). Most plant-based and fungi-based alternatives do not only tend to be low in bioavailable protein and essential amino acids, they also usually deliver inferior amounts of certain vitamins and minerals that are typically higher in meat and other foods from animal origin (in particular iron, zinc, and vitamin B12; Beal et al., 2026). For instance, a study of German college students demonstrated that reliance on "plant-forward" diets incorporating alternative proteins aggravated the inadequate intake of certain micronutrients (Fedde et al., 2025). When comparisons account for micronutrients, relative footprints of plants appear closer than protein-only assessments suggest, although foods from animal origin generally retain somewhat higher emissions (Katz-Rosene et al., 2023). In other words, higher GHG intensities of foods like meat and dairy can be partially offset by a superior nutritional density (Drewnowski et al. 2015; McAuliffe et al. 2020b).

Lastly, alternative proteins are mostly formulated as ultra-processed foods (UPFs), which raises concerns regarding long-term health implications (beyond the effect of inferior micronutrient profiles). Most "plant-based" meat substitutes are formulated as nuggets, burger patties, balls, sausages, and breaded items, while relying on protein isolates and concentrates, refined oils, elevated levels of salt, and a wide array of additives designed to replicate meat-like sensory properties (Bohrer, 2019; Pingali et al., 2023). Reduced consumption of animal-sourced foods can therefore be associated with a higher proportional energy intake from UPFs, for instance in school meal programs (Gehring et al., 2021; Pettersson et al., 2024). Any efforts to increase the consumption of plant-derived proteins would benefit from prioritizing minimally processed beans and lentils, which tend to have more favourable health and environmental impacts.

Carbon costs of public health impacts

These observations raise the broader issue of poor diets and their health-associated C costs. The pharmaceutical sector's emissions exceed those of the automotive industry in intensity (Belkhir & Elmeligi, 2019), whereas the impact of the health care sector in the US has been estimated at 10% of total national GHG emissions (Eckelman & Sherman, 2016). By increasing long-term demand for healthcare services, pharmaceuticals, and medical devices, poor diets act as indirect C multipliers through repeated and energy-intensive medical interventions (Adesogan et al., 2020), with whole (non-ultra-processed) animal-sourced foods having well-documented roles in diets aiming at the prevention of malnutrition, sarcopenia, and diet-related frailty, particularly in vulnerable population groups (Leroy et al., 2022). Obesity further amplifies footprints via increased metabolic energy requirements, higher food intake, and mobility costs (Magkos et al., 2019). Furthermore, because UPFs account for one-third of diet-related emissions among adults in high-income countries (Anastasiou et al., 2022), their reduced consumption, including animal-sourced as well as plant-based UPFs, may lead to emission reductions that are at least comparable to plant-based shifts (e.g., -0.6 kg CO_2e per person, as shown for populations with metabolic syndrome; García et al., 2023).

From this perspective, the assessment of public health-related C costs is highly relevant for evaluating livestock supply chains. Neglecting this in sustainability assessments may lead to an overestimation of the climate benefits of dietary substitutions that rely heavily on nutritionally poor or UPF-like alternative proteins, while underestimating the potential indirect C costs associated with deteriorating public health outcomes (Pulina et al., 2022).

Correcting for co-products

When contextualizing GHG accountancy based on nutritional aspects, as outlined above, additional efforts are needed to factor in edible components other than meat, dairy, and eggs, including co-products (also referred to as "offal"). In lamb production, co-products account for about 1/4th of the total edible product (by weight), 1/5th of total protein, 1/3rd of total fat, and nearly half of total iron. Liver alone contains more vitamin A, B9, and B12 than the carcass and all other co-products combined (Wingett & Alders, 2023).

The argument goes even beyond nutritional considerations, as LCAs of animal-sourced foods should also equitably allocate GHG emissions among the valuable non-edible outputs of livestock production, such as hides, wool, bones, serum, manure, rendered fat and protein meal, and draught power (Alao et al., 2017; Mullen et al., 2017; Lynch et al., 2018; Katz-Rosene, 2020; Lee et al., 2025). Accounting for such products comes with its own complexities, in particular with respect to biogenic carbon flows (Blignaut et al., 2026).

Globally, including in Western markets, the economic and material value of such animal by-products (both edible and inedible) is substantial (Marti et al., 2011; McAllister et al., 2025). Appropriate allocation methods are therefore required to fairly distribute environmental burdens across the multiple functions and market uses of these co-products (Chen et al., 2017; Le Féon et al., 2020; Halpern et al., 2025). Assigning the entire upstream environmental burden exclusively to meat or milk is methodologically inconsistent, as it systematically overestimates the C footprint of the main product and neglects the contribution of other marketable outputs (Ardente & Cellura, 2012; Wilfart et al., 2021).

However, the practical implication of such corrections is hindered by their inherent complexity. In LCAs, this requires a hierarchical approach whereby allocation should first be avoided through system expansion or subdivision where feasible and applied only when unavoidable. Moreover, not all outputs qualify as co-products, as they need to represent independent and positive market value, in contrast to waste. A paradigmatic example is the anaerobic digestion of livestock manure, which goes beyond the mere valorisation of a waste stream by contributing to a reduction of the net C footprint of livestock systems through three concurrent mechanisms: mitigation of direct GHG emissions from manure management, substitution of fossil C via renewable energy production, and the use of digestate as an organic fertiliser, thereby reducing the need for synthetic N fertilisers and their associated upstream emissions. Beyond energy recovery, livestock supply chains also generate a range of high-value technical and pharmaceutical co-products, including collagen derivatives, heparin, and biological materials for medical devices, whose independent market value and functional specificity justify their treatment as co-products rather than waste (Lee et al., 2025).

Outcomes also largely depend on the chosen allocation approach, because economic and mass allocation methods may yield contrasting outcomes. In the case of pet food, another major by-product of meat industries, an economic allocation model seems more appropriate than mass allocation (leading to an overestimation) or treating pet food as simple waste (underestimation) (Alexander et al., 2020). For commercial dog food in the UK, the production of ingredients alone (excluding storage, distribution, etc.) contributes approximately 2–4% of the food system's GHG emissions (1% of total emissions) when using a combination of economic and mass allocation approaches. Without any allocation method, this contribution rises to 6.5% of the food system's total emissions (Harvey et al., 2026).

Yet, even if robust and equitable allocations in multi-output livestock systems are challenging to achieve, their consistent integration into LCAs would reduce the current C footprint of meat to a more accurate estimate, based on the value it co-creates. However, in the overall scheme of things, such reductions may be significant yet modest.

Carbon sequestration and pathways to net zero emissions

The role of grazing lands in C removal

The previous sections were limited to discussing GHG *emissions* by livestock. However, for a realistic evaluation of livestock's net climate impact, its potential for atmospheric C *removal* also needs to be considered (Frankelius, 2020). This is particularly relevant for ruminant systems, given the massive storage of soil organic C in grasslands. Covering nearly half of the land surface, grazing lands account for 10–30% of the global terrestrial soil organic C stock, having played a pivotal role in long-term climate regulation due to their co-evolution with large herbivores (Schuman et al., 2002), to the point that their expansion may have contributed to global cooling and Pleistocene glaciation events (Retallack, 2013). However, during the Late Pleistocene, megafauna extinctions shifted vast steppe ecosystems to less productive tundra, with cascading effects on CH_4 budgets (Zimov et al., 1995; Zimov & Zimov, 2014; Smith et al., 2015). More recent anthropogenic impacts also had profound effects, as for the reduction of North America's prairie ecosystem to 1–2% of its original extent due to land conversion and bison extirpation (Mackelprang et al., 2018).

Therefore, LCAs of ruminant systems should not uncritically portray the sector as a major emitter without adequately accounting for the fact that livestock farmers are the custodians of vast carbon-rich reservoirs within their grazing lands and that emissions can be (at least partially) offset, especially in regions where grasslands dominate the landscape and favourable grazing management is in place (Conant et al., 2017; Viglizzo et al., 2019; Frankelius, 2020). Practically, soil organic C stocks can be enhanced based on wildlife-mimicking methods (adaptive rotational grazing), with high offsetting potential in biome-dominant areas based on complex interactions involving herbivory, animal excreta (saliva, dung, urine), root exudates, and soil microbial communities (Bardgett et al. 1998; Wilson et al. 2018; Hillenbrand et al. 2019; Neal et al. 2020; McAuliffe et al. 2020a). However, sequestration potential is highly context-dependent and inadequate management leads to depletion instead (Chang et al., 2021; Beillouin et al., 2023; Jordon et al., 2024).

Quantifying the sequestration potential and criticism

The COP28 roadmap of FAO (2023) emphasizes the need for an additional 10 Gt CO_2e of sequestration in croplands and pastures between 2025 and 2050, so that agrifood systems can serve as net C sinks. Full global offsetting of livestock CH_4 and N_2O emissions has been dismissed as unlikely by some (Wang et al., 2023), although the overall validity of the assumptions underlying this conclusion requires further inspection and research with regard to the emission scenario adopted, the climate model used, and the atmospheric complexities related to biogenic methane (cf. Section "Biogenic CH_4 and atmospheric complexities"). Rangeland ecosystems and pastoralist systems can nonetheless achieve major partial offsets and become net C sinks in at least some cases (Allard et al., 2007; Beauchemin et al., 2011; Teague et al., 2016; Reyes-Palomo et al., 2022). Reported yearly sequestration rates on rangelands achieve 0.1–0.6 t C/ha under improved management, with higher values of 2–3 t C/ha in adaptive rotational systems and with outliers up to 8 t C/ha when converting degraded cropland (Schuman et al., 2002; Conant et al., 2001, 2003; Liebig et al., 2010; Pelletier et al., 2010; Lupo et al., 2013; Wang et al., 2015; Stanley et al., 2018; Machmuller et al., 2015; Rowntree et al., 2020).

Despite such documented evidence of benefits, soil C sequestration via grazing is often overlooked in assessments due to data limitations. For instance, methodological uncertainties and the fact that conclusions are derived from individual case studies conducted under specific environmental conditions, such as carbon-depleted soils, and over relatively short experimental periods, lead to effects that are potentially transitional and temporary, hampering extrapolation to landscape or global scales. Bradford et al. (2025) noted that, while grassland soil carbon sequestration is a promising climate mitigation strategy, long-term empirical datasets of scale will be necessary for validating and parameterizing management impact on soil carbon outcomes. Thus, nuanced, longitudinal experiments *versus* outright dismissal are warranted to more aptly understand grazing land management impact on soil carbon sequestration. Currently, perceived constraints are often related to: (1) increased land requirements, (2) time-limited sequestration and assumed equilibrium, and (3) higher CH_4 emissions from grass-fed systems due to lower digestibility.

Firstly, although extensive grass-based systems require more land than intensive alternatives, vast degraded areas with herbivore deficits offer ample restoration opportunities, particularly on soils unsuitable for cropping (Yang et al., 2019; Rowntree et al., 2020). Moreover, adaptive rotational grazing can increase stocking densities by 30–50%, partially mitigating land demands (Hillenbrand et al., 2019; Cunningham, 2021). It is also important to reflect on land use potential when assigning land use intensity. The use of land unsuitable for growing crops via grazing systems supports the value of extensive grass-based ruminant systems from a land use efficiency to produce food (key nutrients) perspective, as well as from a C intensity per unit of food produced perspective, especially when corrected for nutritional density (Lee et al., 2021).

Secondly, the saturation argument that mineral-binding sites limit accrual is challenged by evidence of multilayered mineral-associated organic C accumulation without detectable upper limits in temperate soils (Begill et al., 2023) or when experiencing a continuous supply of large amounts of organic inputs (Heinemann et al., 2025). Practitioner observations, such as rapid topsoil formation (e.g., 30 cm in 10 years on challenging substrates; Williams, 2018), further suggest that biology-driven deep sequestration exceeds conventional models. Even so, net-positive annual accumulation of "labile" C from organic inputs (dead plant material and manure) within top-soil still results in C removal and storage even if not mineralised. As such, on-farm C budgets need to be assessed regularly to better understand the full potential of different C stocks, i.e., as soil-mineralised (recalcitrant), soil organic labile (shallow and at depth), and net primary production (plant biomass).

Thirdly, even if higher CH_4 from grass-fed cattle reflects feed digestibility and longer animal lifespan differences, these systems also reduce external feed inputs, which are generally linked to increased land use change and soil C emissions, as well as associated fossil fuel emissions (Reyes-Palomo et al., 2022; Picasso et al., 2014) and are more efficient users of land as they use significantly less arable land (see above, Lee et al., 2021). Moreover, most grain-finished cattle graze extensively beforehand, allowing integration of regenerative practices into the system.

That said, a key concern remains the limited extent to which substantial C sequestration results obtained under specific conditions (adaptive multi-paddock grazing being frequently cited) can be credibly measured, extrapolated, and durably implemented at landscape, national, or global scales in the prevailing ecological and socio-economic contexts of the West and elsewhere.

Ecological considerations: natural baseline emissions and afforestation

Carbon opportunity costs

Discussions surrounding the GHG emissions by livestock sometimes refer to the concept of "C opportunity costs", which include the foregone potential for C sequestration that could be achieved through ecosystem restoration to "natural" vegetation, through rewilding or the large-scale afforestation of agricultural land (Hayek et al., 2021). Proponents of this approach argue that shifting away from animal agriculture could unlock substantial C sinks, whereas others argue that C removal potential of nature-based restoration and the withdrawal of land from production is modest in terms of its ability to meaningfully reduce peak global temperatures in the near term (Dooley et al., 2022).

From an economic and institutional perspective, the conditions under which C removal can be credibly measured, verified, and monetised are not straightforward. In practice, this only acquires climate relevance when embedded within functioning incentive structures, such as compliance or voluntary carbon markets, that impose constraints related to additionality, permanence, leakage, and measurement, reporting and verification (MRV), while exposing land managers to transaction costs, price volatility, and regulatory uncertainty. Moreover, land-based sequestration competes with alternative land uses not only ecologically but also economically, implying foregone agricultural income, weakened rural livelihoods, and the loss of multifunctional agroecosystem services. Framing livestock removal as a prerequisite for C sequestration tends to ignore the potential for integrated C-farming strategies such as silvopasture, in which grazing systems contribute simultaneously to food production, C storage, and ecosystem services, allowing sequestration to function as a complementary revenue stream rather than as a substitute for agricultural activity. Moreover, the capacity of managed grasslands to deliver measurable soil C gains under appropriate grazing regimes may even come at lower cost and with fewer ecological trade-offs than large-scale afforestation or rewilding (Maree et al., 2025).

Many of the targeted areas are "open" ecosystems by nature, and - unless grazed - so much of such afforestation efforts will fail due to burning and remain in a "rangeland" state, rather than in a "forest" state (Bond, 2019; Pausas & Bond, 2020; Czyzewski et al., 2026). Additionally, classification of land uses can be subjective, as Mottet et al. (2017) noted much of Northern Great Plains in the United States and Canada could be classified as grasslands with livestock suitable for arable farming. However, this region is also the focus of conservation efforts to prevent the conversion of native rangelands to croplands to preserve wildlife habitat and other ecosystem goods and services (WWF, 2024). Thus, which lands are best suited to arable farming and plant-based food production *versus* animal-sourced food production can be complex and dependent upon value judgments.

Therefore, C opportunity-cost modelling is not only naïve about real-world land-use conversion, while undervaluing the C storage capacity of managed grasslands by assuming that all pastureland can be converted to high-C forests without considering local ecological constraints, it also overlooks the fact that rewilding and afforestation can have their own perverse effects and that silvopasture based systems often offer both food production as well as C storage potential.

Rewilding and natural baselines

Rewilding scenarios envision replacing livestock with native herbivores, which are less efficient at converting feed into biomass and generate their own enteric CH_4 emissions, complemented with decomposition processes and other biogeochemical pathways (Manzano & White, 2019; Manzano et al., 2026). Moreover, large wild herbivores can reduce net forest C sequestration through browsing and trampling, as shown for moose in Norway, although some of this effect is offset by changes in surface albedo (Salisbury et al., 2023). As a result, anticipated GHG reductions from rewilding may be lower than commonly projected.

Contemporary CH_4 emissions from livestock are comparable to pre-industrial and even deep-historical levels generated by wild herbivores, and especially the megafauna of the Pleistocene (Doughty & Field, 2010; Hristov, 2012; Zimov & Zimov, 2014; Smith et al., 2015; Czyzewski et al., 2026). Even since the mid-19th century, the warming effect associated with livestock herd increases has been partially compensated by a decline in wild grazer numbers (Chang et al., 2021).

Therefore, a critical implication of these findings is that natural herbivore baselines have been systematically underestimated and their effect often overlooked. In “open” ecosystems, including vast areas in North America and parts of the European temperate forest biome, ecological herbivory has long been a natural feature (Pearce et al., 2023). Domestic herbivores should therefore be viewed, at least in part, as functional replacements for extinct or extirpated wild populations (Czyzewski et al., 2026). This challenges the common attribution of all livestock-related emissions as purely anthropogenic, as part of that budget would be filled in by natural emissions, especially in extensive pastoral systems which are now unfairly stigmatized as “inefficient” and, therefore, polluting (Manzano et al. 2023a, b). Data from Spain has shown a herbivore baseline equivalent to 23% of current enteric CH_4 emissions from grazing livestock (Serrano-Zulueta et al., 2023), whereas the coupling of natural baselines to a lower reliance on external feeds in extensive systems pushes C footprints of traditionally managed transhumant Spanish lamb below that of intensive lamb systems (Pardo et al., 2024).

Afforestation scenarios

Deforestation driven by livestock expansion contributes to climate change, with emissions from conversion to pasture being concentrated primarily in South America (around 70%) and East/Southeast Asia (around 20%) (Chang et al., 2021). Where ecologically appropriate, targeted reforestation is warranted. Nevertheless, calls for ambitious global afforestation programs through C-credit incentives, predicated on high theoretical sequestration potentials, must be tempered by practical and ecological realities. When ill-conceived, they lead to biodiversity losses, reductions in ecosystem services, elevated risks of large-scale wildfires in Mediterranean and semi-arid regions, and an increased vulnerability to climate change (Choat et al., 2012; Veldman et al., 2015; Dass et al., 2018; McClure, 2023). Moreover, the C sequestration advantage of new forests materializes only after decades or centuries (Poeplau et al., 2011; Friggens et al., 2020), with altered aerosol dynamics and albedo offsetting a substantial portion of the expected benefit, even generating a net warming effect in certain contexts (Kirschbaum et al., 2011; Weber et al., 2024). Conventional forest management practices often prove ineffective for long-term C sequestration (Naudts et al., 2016), as shown through satellite-based analyses in regions such as California (Coffield et al., 2022).

Converting grasslands to forest does therefore not invariably increase soil organic C stocks (Beillouin et al., 2023), with permanent grasslands often comparing favourably to temperate forests. Well-managed grazing systems can sequester C at rates comparable or superior to early-stage afforestation (0.5 t C/ha/year during the first two decades) (European Commission, 2020), doing so at greater soil depths (> 1 m) due to extensive root systems, in contrast to surface-oriented accumulation in secondary forests (Wei et al., 2012). In regions prone to wildfire, deeper soil C pools in grasslands also offer greater resilience than aboveground forest stocks (Dass et al., 2018; Stevens & Bond, 2024).

Grasslands and trees are not mutually exclusive

To be clear, the argument outlined above is not one against afforestation as such, but against inappropriate tree-centric policies. Rather than pursuing the wholesale displacement of livestock through afforestation, a more resilient approach involves the strategic integration of woody vegetation within farming systems through agroforestry and silvopastoralism, as mentioned above. As such, meaningful C sequestration can be obtained without eliminating grazing animals, while creating ecological co-benefits (De Stefano & Jacobson, 2018; Plexida et al., 2018; Assouma et al., 2019). Moreover, targeted livestock grazing serves as an effective tool for fuel-load reduction and wildfire prevention (Lasanta et al., 2018).

In Spanish dehesa systems, tree and soil C sequestration offsets 54% of emissions on conventionally managed cattle farms and 95% on organically managed ones, occasionally yielding negative net C footprints (Reyes-Palomo et al., 2022). Similarly, in Mediterranean cow–calf systems characterized by low cultivation intensity and extensive silvopastoral land use, soil, and woody biomass sequestration were sufficient to offset a large share of on-farm GHG emissions, in some cases yielding negative net C footprints at the farm-gate level (Lunesu et al., 2026). In Sardinian dairy sheep farms, the inclusion of soil C sequestration reduced product-level emission intensities by a third, substantially lowering the net C footprint across milk and co-products when emissions and removals were jointly accounted for (Lunesu et al., 2025). On New Zealand sheep and beef farms, non-forest woody vegetation can offset 30–90% of on-farm agricultural emissions, depending on the study and methodology (Mazzetto et al., 2023; Case & Ryan, 2020). Although most on-farm woody vegetation does not currently qualify as "forest" under national GHG inventories, recognizing its sequestration contributions would represent an important step toward fairer accounting and incentivization of sustainable land management.

Biogenic CH_4 and atmospheric complexities

Ruminants *versus* monogastrics: not only about CH_4

Ruminants generate higher GHG emissions per unit of food produced compared to other livestock categories, primarily due to enteric CH_4 production, having a greater short-term warming potency than CO_2. However, a simplistic substitution of ruminants with monogastric animals or other protein sources overlooks several important factors. Accurate comparisons must incorporate farm management practices (Nijdam et al., 2012) and the differing nutritional profiles of various meat types (McAuliffe et al., 2018). Moreover, when accounting for avoided land-use change and the release of cropland previously dedicated to feed production, a partial shift in global livestock production towards ruminants could potentially reduce overall emissions of GHGs and nitrogen (Cheng et al., 2022). In addition, provinces of France which had higher proportions of ruminant livestock were shown to be more efficient at providing nutrients to support human health per unit of arable land use than provinces which had a higher proportion of monogastric livestock, due to the ability of ruminants to use resources and land that does not directly compete with crop production (Lee et al., 2021).

It is also important to bear in mind that ruminant CH_4 recycles existing atmospheric C through a biogenic cycle and does not introduce "new" C as with burning fossil fuels. Consequently, fossil fuel-derived CH_4 emissions have a fundamentally more persistent climate impact than a stable biogenic CH_4 flux, requiring the use of appropriate metrics in mitigation scenarios and policies (Ridoutt 2024a).

Global warming potential metrics

Assessments of ruminant CH_4 are usually based on the conventional 100-year Global Warming Potential (GWP100) metric, which must be interpreted with caution given the fundamental differences in atmospheric kinetics between CH_4 and CO_2. Conventional GWP100 treats pulses of both gasses using the same framework, equating their potential warming effects over a future 100-year horizon, although the former is a short-lived flow climate pollutant and the latter functions as a long-lived stock pollutant that accumulates over centuries. This distinction has prompted the development of GWP*, an alternative metric that better reflects the dynamic, time-dependent warming impacts of short-lived gases and aligns more closely with climate model projections when viewed within a common cumulative emission framework (Cain et al. 2019; Lynch et al. 2020; McAuliffe et al. 2023b). Under GWP*, stable or slowly declining methane emissions from ruminants result in lower estimated additional warming contributions compared to conventional GWP100 (del Prado et al. 2023b). However, the opposite occurs when methane emission rates increase dramatically, leading to an underestimation of the additional warming impact.

Where ruminant CH_4 emissions remain stable they do not significantly contribute to additional global warming, as CH_4 destruction in the atmosphere roughly balances new production (provided no net increase occurs). A modest and sustained annual reduction of ~0.3% in herd CH_4 emissions could stabilize their future effect on global temperature, while greater reductions would reverse historical past contributions to global warming by the sector in a similar fashion to increasing C sinks (del Prado et al. 2023a). Building on this conceptual framework, modelling has shown that the choice of emission metric has profound implications for the estimated amount of CO_2 removal required to offset livestock-related CH_4 and N_2O emissions under future scenarios (Correddu et al., 2025). In well-managed grazing systems, characterized by healthy soils, carbon sequestration, adequate grass cover, and sound land management practices, the selection of metric can indeed determine whether ruminant livestock acts as a net source or net sink of greenhouse gases (Blignaut et al., 2022; Reinecke et al., 2026). While conventional GWP100 systematically misrepresents the removal needed to achieve a condition of no additional warming, GWP* provides estimates that are more consistent with temperature-based climate goals (i.e., Paris Agreement), particularly under constant or declining CH_4 emission pathways.

This distinction is critical for interpreting net-zero strategies. In regions with decreasing CH_4 levels, as is common in many parts of the global West, agricultural emissions calculated via GWP* thus represent only a fraction of GWP100-based values. A New Zealand study found that, when incorporating C sequestration and applying GWP* over the period 1998–2018, sheepmeat appeared climate-neutral (understood as a situation in which human activities cause no additional increase or decrease of the global average surface temperature; Allen et al., 2022), while beef production was trending toward neutrality, contrasting sharply with higher footprints under GWP100 (Mazzetto et al., 2023). Similarly, in Australia, sheepmeat production was reported to have a negative GHG footprint when assessed using GWP*, a finding equivalent to CO_2 removal (Ridoutt, 2021a). In Ireland, combining mitigation strategies with GWP*-assessments may substantially offset CH_4 -related warming by 2050 without sacrificing productivity (McKenna & Banwart, 2024).

Radiative forcing (RF) footprints are another way of assessing GHG emissions. Using the same equations that are used to calculate GWP100, they report RF from current year emissions, together with the RF from historical emissions that remain in the atmosphere (Ridoutt, 2021b). Like GWP*, the climate impacts of emissions with short and long atmospheric lifetimes are clearly differentiated. Using this approach, RF footprints support the management of emissions toward the goal of making no additional contribution to increasing global GHG concentrations, demonstrating realistic pathways for the Australian red meat industry to achieve and maintain climate neutrality (Ridoutt, 2024b, 2024c).

However, even if the notion of reducing short-lived biogenic emissions to “buy time” for later CO_2 mitigation could make the goal of climate stabilisation more elusive, CH_4 concentrations continue to rise globally, with agriculture (e.g., livestock enteric fermentation and anaerobic soils), mining and waste (e.g., natural gas leaks and landfill), and natural emissions (e.g., wild-herbivore enteric fermentation, soil and permafrost melting) representing ca. 30, 30, and 40%, respectively, of global emissions.

Moreover, the GWP* framework raises important issues of climate equity between high- and low- and middle-income countries, thereby skewing the perception of responsibility. In brief, an accountancy advantage for established emitters would be created, while burdening those developing nations that are seeking to increase agricultural output, thus facing a more heavy penalization of their new emissions. As such, all sectors must continue work to reduce emissions to buy time on CO_2 reduction which will ultimately require transition from fossil-fuel use, the primary cause of anthropogenic global warming.

It should be noted that the IPCC Sixth Assessment Report continues to use GWP100 as the standard metric for aggregating greenhouse gas emissions. At the same time, it discusses alternative approaches for representing the climate effects of different gases, including GWP*. The treatment of metrics for short-lived climate forcers is under further methodological consideration within the ongoing IPCC assessment cycle, including in the forthcoming Methodology Report on Short-Lived Climate Forcers (IPCC, 2021, 2023). In parallel, international assessments of food systems have begun to examine the application of alternative methane metrics. For example, the FAO report on methane emissions in livestock and rice systems considers the use of GWP* when analysing emission pathways and time series, while emphasising that methane mitigation must remain compatible with the need to expand food production in many low- and middle-income countries (FAO, 2023c).

As metrics such as GWP100 and GWP* provide different information, i.e., carbon emission equivalents (how much carbon dioxide equivalency is built up in the atmosphere) *versus* warming equivalents (how the gases impact on global warming), it is recommended to report them side-by-side instead of usurping or replacing one another (McAuliffe et al., 2023b).

What explains current CH_4 increases?

Recent surges in atmospheric CH_4 concentrations (post-2007 and particularly post-2014) appear attributable to a combination of factors, including expanded livestock production in lower-efficiency regions, but also substantial contributions from fossil fuel extraction (e.g., shale gas and major leaks), landfills, rice cultivation, wetlands, permafrost melt, and natural or semi-natural microbial sources (Nisbet et al., 2016; Alvarez et al., 2018; Etiope & Schwietzke, 2019; Jackson et al., 2020; Rosentreter et al., 2021; Skeie et al., 2023; Qian et al., 2023; Ciais et al., 2026). Declining atmospheric sinks (e.g., reduced hydroxyl radical levels influenced by carbon monoxide, CO) may also play a role (Turner et al., 2017; Cheng & Redfern, 2022; Wang et al., 2022; Skeie et al., 2023; Ciais et al., 2026). The interplay between hydroxyl radical levels and CO in the coming decades will therefore influence CH_4’s future climate forcing (Liu et al., 2024), and better models will need to be developed to explain atmospheric CH_4 accumulation beyond what is ascribed to livestock agriculture (Ederer & Iliushyk, 2025).

Conclusion: transcending carbon tunnel vision

Taken together, today's discourse on sustainable meat production in the West suffers from "carbon tunnel vision", a myopic perspective which overemphasizes GHG emissions as the primary metric for evaluating environmental impacts, while overlooking the various complexities summarized in the present article. This also comes at the expense of more comprehensive assessments that include effects on biodiversity, water resources, soil health, socioeconomic factors, and human and animal wellbeing (ALEPH2020, 2026). Although reducing emissions from livestock agriculture remains a legitimate priority, fixating solely on C metrics leads to suboptimal interventions, potentially worsening some of the other environmental impacts of livestock agriculture, and to the scapegoating of livestock as destructive GHG emitters. A further implication is that climate-oriented livestock policies must be grounded in metrics and accounting frameworks that are physically meaningful and aligned with temperature-based climate goals. Treating biogenic CH_4, fossil CO_2, and C removal as interchangeable flows under conventional accounting obscures their fundamentally different atmospheric behaviours and risks misallocating mitigation efforts. This directly affects the estimated scale of CO_2 removal required to avoid additional warming, with important consequences for the feasibility, cost, and perceived responsibility of livestock systems. Ignoring these distinctions reinforces C tunnel vision and may lead to policies that penalise CH_4 -intensive but potentially net-mitigating systems, while diverting attention from fossil C dependence and from realistic, system-integrated mitigation pathways.

Mitigation of global herd emissions is achievable without compromising meat availability, by prioritizing efficiency gains at the production level. When policies start emphasizing blanket reductions in animal-sourced foods intake, only modest global emission cuts are to be expected, while overlooking nutritional trade-offs. Any policy promoting modest emission reductions at the expense of human health is unacceptable. Transitioning towards lower-emission diets is to be recommended, but must not neglect nutrient security and avoid unintended consequences, especially for vulnerable groups. Instead, policies should target ecosystem restoration and use balanced metrics incorporating evidence-based ecological targets alongside emissions goals. Improved integration of agroecological principles, such as crop-livestock integration, legume-based rotations, silvopastoralism, agroforestry, and adaptive multipaddock grazing, will help to create multiple beneficial outcomes while closing nutrient cycles and minimizing external inputs.

To transcend C tunnel vision, context-specific strategies and landscape-level collaborations among stakeholders who value livestock's multifunctional roles in sustainable food systems will need to be introduced with urgency yet in a sufficiently cautious manner, as not to lead to food system dysfunction and harmful nutritional, economic, ecological, or social harms. To do so, research and policy innovations will be needed at multiple levels, not in the least including metrics reform and more productive incentive structures.

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Declarations

Competing interests The authors declare no financial conflicts of interest relevant to this manuscript. Nonetheless, for full transparency, Frédéric Leroy reports non-remunerated membership of scientific boards of the Belgian Association for Meat Science and Technology (non-profit academic society), Belgian Nutrition Society (non-profit academic society), Belgian Society for Food Microbiology (non-profit academic society), World Farmers' Organization, Food and Agriculture Organization of the United Nations, and the European Parliament's Sustainable Livestock Intergroup. Ty Beal declares no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Frank R. Dunshea is a member of the board of Australian Pork Research Limited and Animal Production Science and reports non-financial support from the World Association for Animal Production and non-financial support and travel reimbursement from PigWeb. Peer Ederer reports funding from governmental and commercial sources to support the research program at GOALSciences (those sources are confidential, none of them have influence on the research agenda) and non-remunerated membership of the scientific boards of the World Farmers' Organization and the European Parliament's Sustainable Livestock Intergroup. Michael R. F. Lee reports non-remunerated membership of scientific boards of the Food and Agriculture Organization of the United Nations, UK Department for Environment Food and Rural Affairs, World Farmers' Organization, and the European Parliament's Sustainable Livestock Intergroup. Pablo Manzano reports non-remunerated membership of scientific boards of Trashumancia y Naturaleza, the World Farmers' Organization, the Food and Agriculture Organization of the United Nations, and the European Parliament's Sustainable Livestock Intergroup. Frank Mitloehner reports a relationship with the UC Davis CLEAR Center as Director; he also reports funding from a variety of public agencies, commodity groups, and private-sector organizations within the agricultural and animal health sectors to support research on livestock production systems; all research funding is administered through the University of California, Davis, under established institutional policies that ensure investigator independence and academic integrity. Sara Place reports a relationship with Dairy Management Inc that includes board membership and funding of grants, scientific board membership at the Food and Agriculture Organization of the United Nations, and funding grants from the Grantham Foundation for the Protection of the Environment, US Department of Agriculture, State of Colorado Department of Agriculture, California Department of Food and Agriculture, Gerstner Family Foundation, NSF Ascend Engine, Elanco Animal Health, Cargill Inc, Zoetis Inc, and American Hereford Association. Agustin del Prado reports financial support provided by Provacuno and Lactalis. Giuseppe Pulina reports non-remunerated membership of the scientific boards of the World Farmers' Organization and the European Parliament's Sustainable Livestock Intergroup; he is the non-remunerated president of the non-profit association Carni Sostenibili (Sustainable Meat), which provides information on responsible consumption and sustainable and ethical meat production through media activities based strictly on scientific evidence. Brad Ridoutt has undertaken food systems research related to environmental issues for a variety of private sector organizations and Australian government agencies (including Dairy Australia and Meat and Livestock Australia). Jason Rowntree reports a relationship as non-remunerated scientific advisor for the Meat Institute (USA) and membership of the US Roundtable for Sustainable Beef. None of the authors' advisory roles mentioned did influence the conception, interpretation, or conclusions of this manuscript.

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