Opportunities for Improving Productivity and Reducing Methane Emissions in Smallholder Dairy Systems in Low- and Middle-Income Countries

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PxD PRECISION DEVELOPMENT

IGSD

October 2024

Initiative Overview

Precision Development (PxD) and the Institute for Governance & Sustainable Development (IGSD) are partnering on a unique initiative to collaboratively identify opportunities for innovation in climate change mitigation, particularly for the greenhouse gases most problematic in agricultural production, methane, and nitrous oxide, as well as carbon dioxide. We are specifically focused on innovations with pertinence to the world's smallholder farmers, who farm most of the world's approximately 570 million farms. The Food and Agriculture Organization of the United Nations defines these smallholder farmers as "small-scale farmers, pastoralists, forest keepers, fishers who manage areas varying from less than one hectare to 10 hectares…(and) are characterized by family-focused motives such as favouring the stability of the farm household system, using mainly family labour for production and using part of the produce for family consumption." The majority of farms in the Global South, a term used to denote the regions of Asia, Latin America, Africa, and Oceania, are small and it is within this broad geography and smallholder farming context that we focus our climate change mitigation initiative.

This initiative includes four analytical pieces on the following opportunities for climate change mitigation by smallholder famers:

- carbon dioxide sequestration through enhanced rock weathering,
- carbon dioxide sequestration through conserving (keeping what is already present) or increasing (i.e., sequestering) the organic carbon storage in soils and plant biomass,
- nitrous oxide mitigation through precision nutrient management, and
- methane mitigation in dairy through improved livestock feeding practices.

In our initiative we are guided by the following principles:

Consider the tradeoffs: We aim to determine smallholder farmers' private returns from the adoption of new technologies or agricultural practices, as well as the societal return of such adoption as measured by gauging the impact of these innovations on our main outcome of interest in climate change mitigation, namely, reducing greenhouse gas (GHG) emissions.

Farmer welfare first: Smallholder farmers cannot be expected to pay the price for climate change mitigation. Climate change-related advisory should support livelihoods, especially as sustained adoption cannot occur without realized benefits for farmers. If it is difficult to understand *a priori* how a specific agricultural practice or technology might impact yields or income, we commit to exploring ways to compensate early adopters as payment for promoting the broader social benefit.

Replicate and scale: We aim to deliver impact at scale. We are particularly interested in low-cost climate change mitigation innovations with strong adoption potential, that can be customized to local contexts, and scaled throughout other regions with similar constraints or needs.

Our goal is to identify opportunities in agriculture with potential benefits for smallholder farmers, either directly or through compensation mechanisms for their environmental services, as well as for GHG mitigation. In identifying these opportunities, we will outline the evidence for impact on farmers' outcomes and on GHG-mitigation outcomes, as well as address challenges in building that evidence, particularly in outcome measurement methods. We will also address practical next steps to build a pathway to scale for the identified opportunities.

About Precision Development (PxD)

Precision Development (PxD) is a global non-profit organization that harnesses technology, data science, and behavioral economics to build digital services that empower people to change their own lives. We build low-cost information systems at scale to share knowledge with the world's poorest and most disadvantaged people. Our pioneering model of digital development is implemented in collaboration with partner organizations to maximize scale. We continuously experiment, iterate, and gather evidence on our impact to improve service delivery and demonstrate our value. Most of PxD's services deliver customized digital agricultural advisory to smallholder farmers, with more than 6 million users using these services in 2022. Given the many constraints facing these farmers, PxD is investigating the application of our platforms and core competencies to deliver advisory in new informational fields, including climate change adaptation and mitigation, as the effects of global warming ripple through the agriculture sector.

About the Institute for Governance & Sustainable Development (IGSD)

The Institute for Governance & Sustainable Development (IGSD) promotes just and sustainable societies, specifically through building resilience by accelerating fast climate change mitigation actions to slow near-term warming and self-reinforcing climate feedbacks, avoid catastrophic climate and societal tipping points, and limit global temperature increase to 1.5 °C—or at least keep this temperature guardrail in sight. IGSD's latest research shows that decarbonization alone is insufficient to slow near-term warming to keep us below 1.5 °C or even the more dangerous 2 °C guardrail, and that the fastest and most effective strategy is to combine the marathon to zero out carbon dioxide (CO_2) emissions by decarbonizing the energy system with the sprint to rapidly cut non-CO_2 super climate pollutants, and to protect carbon sinks. The super climate pollutants include four short-lived climate pollutants (SLCPs)—methane (CH_4), hydrofluorocarbons (HFCs), black carbon soot, and tropospheric ozone (O_3)—as well as the longer-lived nitrous oxide (N_2O).

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Terminology

Anti-methanogenic/Methanogenesis – Methanogenesis describes the microbial process by which methane is produced under anaerobic, or no-oxygen, conditions.[1] Enteric fermentation (i.e., stomach digestion processes)[2] in ruminants produces methane via methanogenesis, which can be suppressed by adding anti-methanogenic supplements to diets.[3]

Enteric fermentation – Ruminants produce methane emissions when microorganisms in their digestive system break down carbohydrates in the ruminant's feed, releasing methane via burps.[4]

Emission intensity (methane intensity) – Methane emissions (grams) per kilogram of product, e.g., milk in the case of dairy cows. See Box 1 for more information on emission intensities, particularly methane intensities, in comparison to absolute methane emissions.

Livestock systems – Systems that raise animals to provide goods or services. These can be classified as pastoral (grassland-based), landless (what is commonly observed in urban and peri-urban systems), or mixed crop-livestock (integrating crops and livestock).[5] Each system will have differing land availability, water availability, intensity of production, type of product, weather and soil conditions, pathways to product commercialization, etc.[6]

Maintenance requirement – Minimum amount of energy needed to maintain animal health and survival. Energy gained beyond the maintenance requirement can result in production of meat (through weight gain) or milk.[7]

Ruminants – Animals, including cattle, buffalo, sheep, and goats, with specialized digestive systems to utilize nutrients from fibrous plant material.[8] These animals have four parts to their stomach, including a rumen, which hosts microbial populations that break down cellulose from their diet.[9]

Spillover effect – Greenhouse gas (GHG) mitigation efforts in one area result in an observed emissions increase elsewhere in the global supply chain.[10] For example, reducing cow herds in industrialized systems through a tax can incentivize increases in herd sizes and emissions in developing countries to make up for supply gaps.[11]

Sustainable intensification – The production of more animal products through sustainable practices (e.g., better feed quality for cattle, higher resource use efficiency) with minimal increase in emission of greenhouse gases per product and minimal use of additional land.[12]

Yield gap – The difference between actual farm yield and the yield potential with improved management practices that minimize losses.[13]

Executive Summary

Methane is second only to carbon dioxide in its contribution to global warming, and accounts for about half of the temperature increase of human-induced global warming (0.51 °C out of the present 1.06 °C).[14] Strong, rapid, and sustained methane reductions are key to slowing warming in the next two decades,[15] thereby reducing the risks of triggering self-amplifying feedbacks (such as thawing of the permafrost in the Arctic[16]) and of crossing irreversible tipping points (including loss of tropical reefs, the Amazon rainforest, the Greenland Ice Sheet, and the West Antarctic Ice Sheet).[17] Growing recognition of the urgency to reduce methane emissions has propelled over 150 countries to endorse the Global Methane Pledge, which sets a collective target to reduce global methane emissions by at least 30% from 2020 levels by 2030. Achieving this target would reduce warming by at least 0.2 °C by 2050 and keep the planet on a pathway consistent with the goals of the Paris Agreement.[18]

Meeting this target will require deep reductions from all anthropogenic sources of methane, including the livestock sector which accounts for nearly a third of global human-caused methane emissions.[19] About 90% of direct emissions from livestock, or emissions directly produced by the animal, come from digestive processes in the rumen of the animal (primarily cattle) in a process known as enteric fermentation. The remaining 10% is associated with manure emissions.[20]

There are four main approaches to reduce methane emissions from livestock:

1. **Increasing the productivity of meat and dairy production**. In low-productivity contexts, this can lead to reduced methane emission intensity (methane emissions per kg of milk or meat produced) and reduced absolute methane emissions, when paired with reducing the overall number of livestock.
2. **Using feed additives or other technology to reduce emissions from enteric fermentation, and maintaining or reducing the number of livestock.**
3. **Investing in alternative proteins (plant-based, fermentation-derived, and/or cultivated meat) as a substitute for animal-sourced foods**,[21] which may ultimately reduce demand for traditional animal products and aid in the reduction of animal numbers.
4. **Reducing emissions, through management of manure.**

The focus of this brief is on identifying methane mitigation approaches currently suitable for implementation in smallholder farmer and pastoralist contexts. Livestock in countries defined by the United Nations Framework Convention on Climate Change as non-annex 1 countries, i.e. primarily low- and middle-income countries (LMIC)[22], contribute 70% of the global non-carbon dioxide (non-CO_2) emissions from ruminants, and this share is expected to increase as the demand for livestock products increases in these countries.[23] While feed additives and technologies for methane inhibition are receiving the most attention and investment, these solutions are unlikely to work for smallholder and pastoral farmers in the short to medium term, due to the cost, the state of commercial availability, and other institutional barriers to accessing and adopting new technologies in LMIC contexts. Similarly, alternative proteins are a longer-term protein substitution solution, in terms of market access and readiness, with adoption in the LMIC expected to lag significantly. Manure management is a demonstrated methane mitigation approach that is partially addressed through reduction in animal numbers. However, it represents a relatively small portion of emissions from the livestock sector.

The primary methane mitigation strategy appropriate for smallholder contexts are interventions that can increase productivity and reduce methane emissions per quantity of milk, while simultaneously reducing animal numbers. Reductions in emission intensity can be assessed by tracking two key variables: quality and quantity of feed consumed, and quantity of milk produced. Higher quality diets and higher feed intake lead to greater methane production per animal, but also to greater milk yield, which reduces the methane emission intensity. Using established relationships between feed quality, feed intake, and the fixed ratio of 20.7 grams of methane emitted per kilogram of food (dry matter intake),[24] methane emissions can be estimated at the farm level to evaluate the effectiveness of feed interventions for climate outcomes.

The recommendations provided in this review follow these general themes: increase productivity and reduce herd size, tailor metrics and markets to incentivize reductions in both total methane emissions and methane emission intensity, provide technical support to farmers and extensionists to increase the uptake of efficient production strategies, and launch pilot projects to test scalable interventions for overcoming barriers to methane reduction strategies.

Increase productivity and reduce herd size:

- Feed: Prioritize strategies that increase productivity at low cost. Improving feed is key to reducing methane emission intensity and it should be an increased focus of development agencies that fund livestock development strategies. Feeding can be improved by using crop residues, strategic supplementation, and cut-and-carry (harvesting of fodder to be fed directly to animals) forages and legumes. Value chains for fodder should be developed in tandem with novel feeds that could reduce methane emissions. This can be done by exploring new cut-and-carry fodders and trees[25] or by developing alternative biomass streams sourced from food waste.[26] Developing value chains is a substantial undertaking requiring effort across public and private sectors. The development of tools, e.g. FEAST from the International Livestock Research Institute, that clearly map out options for smallholder farmers to change feed based on their local context, is needed to support the transition to sustainable feeding. Farms with cattle that yield more product can reach a productivity target with fewer animals than farms with lower productivity, allowing farmers to reduce herd sizes and absolute methane emissions.
- Health: Focus on improved health management and husbandry practices, especially for indigenous animals that make up the majority of herds in smallholder contexts. Improvement in the productivity of existing animals through strengthened health management and access to better feed is fundamental, and should precede cross-breeding schemes which will take longer to be implemented.[27]
- Breeding and services: As access to better feed and veterinary care improves, invest in cross-breeding schemes. Ensure the schemes are adequately planned to maintain a constant supply of inputs like feeds, vaccines, and artificial insemination services.

Tailor metrics and markets to incentivize reductions in total methane emission and in methane emission intensity:

- Reform metrics and targets to achieve low methane emission intensity and low absolute methane emissions from productive systems (e.g., production targets measured in tons of meat and kilograms of milk).
- Create incentives for intensification by investing in market creation and access. In the diary context, for example, this is essential for ensuring incentives exist to intensify milk production, and will require significant infrastructural costs such as dairy cold chains, milk collection hubs, and processing plants. Successful examples in East Africa systematically provide higher volumes of safe milk for a growing market of consumers.[28]

Provide technical support to farmers and extensionists to increase the uptake of efficient production strategies:

- Implement scalable agricultural information systems built on an understanding of farmer incentives and needs, existing markets and states of market access, and on the evidence behind potential interventions for smallholder farmers.[29]
- Train extensionists on the rapid estimation of greenhouse gas (GHG) emissions using simple tools. This will help establish reasonable baselines of productivity and emissions, for improving the monitoring of GHG emissions and identifying the mitigation practices that are most effective in real-world smallholder contexts.
- Invest in training on food safety to ensure that high quality milk reaches consumers, from rural areas.

Design and test incentive mechanisms for overcoming barriers:

- Intentionally plan projects that promote increases in productivity and improvements in livelihoods while reducing overall emissions and improving the environmental performance of livestock systems. Pilot projects should be designed with a potential path to scale in smallholder and LMIC contexts.
- Design and test novel approaches, e.g., carbon finance, to incentivize value chains for fodder, and other approaches such as payments for environmental performance, to amplify the opportunities for adopting more sustainable practices.

1. Greenhouse Gas Emissions from Livestock Systems

The climate crisis is an unprecedented and escalating emergency, with significant impacts on our global food system. The Food and Agriculture Organization's 2023 food security report finds that global hunger levels are rising as a result of climate change shocks.[30] Today, people are experiencing undernourishment and malnutrition at increasing rates, pushing us further from reaching Sustainable Development Goals (SDGs) (e.g., SDG 2: Zero Hunger).[31] Consumption patterns of animal-sourced foods are globally unequal, which adds further complexity to navigating how to feed a growing human population. Low- and middle-income countries (LMICs) are consuming less animal-sourced foods than are nutritionally required. LIMICs are also projected to face future difficulties in supplying animal-sourced foods for their growing populations, given their current yield trends and the consistency of land expansion.[32] High-income countries, on the other hand, often have consumption of animal protein above the recommended dietary level.[33]

To add to this already strained system, human population is projected to increase to 9.7 billion by 2050.[34] With anticipated increases in incomes, and changes in urbanization, nutritional needs, and environmental pressures, food demand is expected to increase by 30–62% by 2050.[35] Meat protein consumption is expected to outpace production in certain countries by 2030.[36] The combined threat of undernutrition and overconsumption presents a global food system that is not well equipped to meet projected needs.

Furthermore, our food system is a major contributor to greenhouse gas (GHG) emissions. Research estimates that the agrifood system contributes to nearly 30% of GHGs.[37] Food system emissions (including food waste) represent 60% of anthropogenic methane emissions.[38] If current food consumption and food production behavior patterns continue, food system emissions alone will probably push us over the internationally-agreed 1.5 °C end-of-century guardrail.[39] Despite future projections of lowered emissions intensities in livestock systems,[40] see Box 1, absolute emissions increases by the end of the century will largely be driven by high-methane foods (e.g., dairy and red meat).[41] Livestock production alone is responsible for 17% of food system emissions (of which cattle account for 65–77%[42]) and 30% of anthropogenic methane emissions.[43]

Given projections in the demand for animal protein, and its contribution to climate change, attention must be focused on livestock production systems to achieve nutrition, development, and climate mitigation goals. As the largest land-use sector on Earth,[44] livestock systems represent a transformational opportunity to sustainably support the protein needs of an increasing population, drive productivity and economic growth in developing regions, and reduce environmental impact through improved efficiency and resource use. Many solutions to the challenges of feeding the world sustainably may be found in how we manage this growing demand in the livestock sector.

Box 1: Functional Units to Assess GHG Emissions from Dairy Production Systems

In contrast to the increasing trend in absolute GHG emissions from livestock, GHG emission *intensities* have decreased globally and are about 60% lower today than in the 1960s, largely due to improved meat and milk productivity of cattle breeds.[45]

Products like red meat remain the most inefficient in terms of emissions per kg of protein produced, in comparison to milk, pork, eggs, and all crop products.[46] However, the functional unit used in these measurements is highly context-dependent and may produce different results.[47] For instance, metrics based on products tend to rate intensive livestock systems (high production on minimal land) as efficient, while metrics based on area or resources used tend to rate extensive systems as efficient.[48] In ruminant dairy systems, low productivity farms show higher emissions if expressed in terms of product, and lower emissions if expressed in terms of utilizable agricultural land.[49]

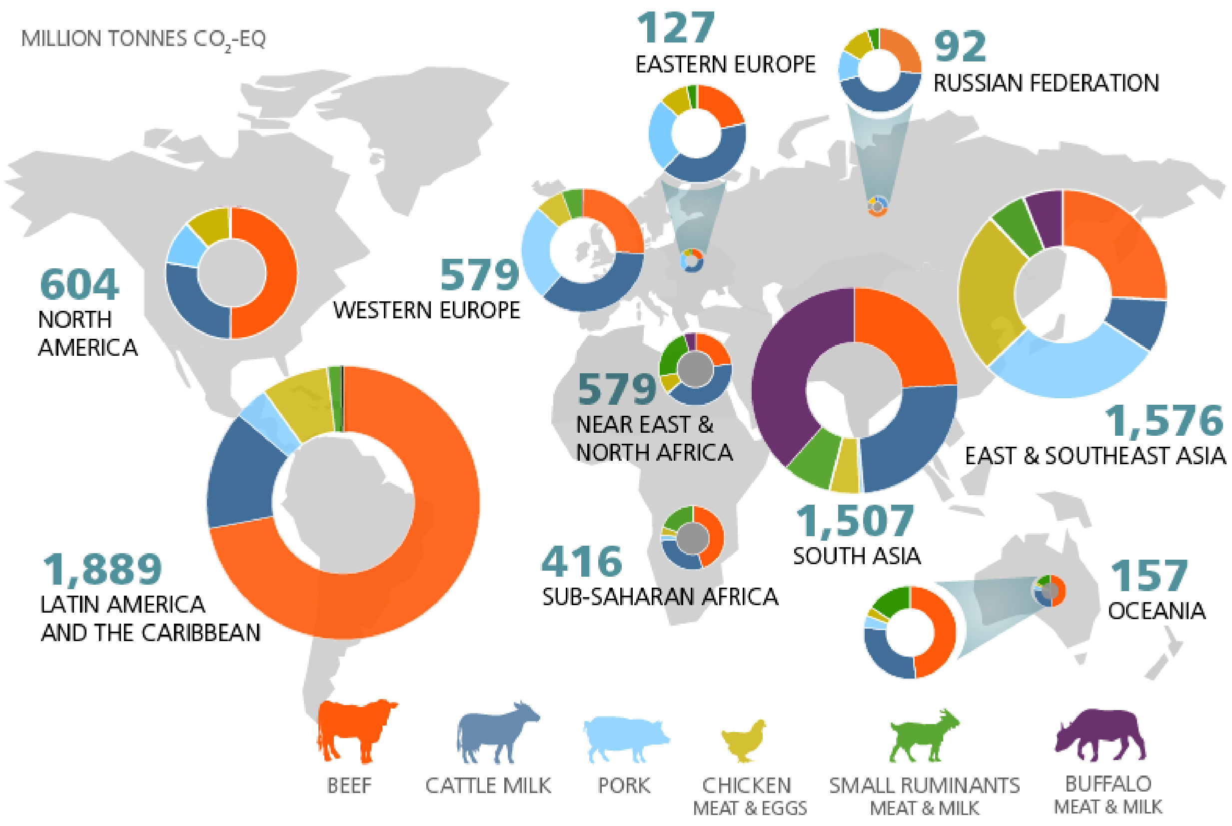
If other variables are used in the analysis of GHG emissions of different ruminant production systems, such as animal feed using human-edible grains instead of crop waste and pastures of marginal lands, or carbon sequestration in pasture systems in degraded lands, then the GHG emissions of extensive systems are reduced.[50] Reductions of 26% and 43% have been shown in extensive systems of small ruminants, such as sheep and goats.[51] Depending on what the main challenge is in different regions (for example, undernourishment, over-consumption, natural resources degradation), different metrics could be used as the reference. Other metrics that consider nutrient density have been proposed because they may achieve both mitigation and health targets,[52] but they address a set of goals not included in this brief.

A. Livestock Systems Are Primary Contributors to Emissions of Non-CO2 Greenhouse Gases, Particularly Methane and Nitrous Oxide

Direct livestock emissions are primarily non-carbon dioxide (non-CO_2) greenhouse gases. Enteric fermentation from ruminants produces methane via microorganisms in ruminants' digestive systems. The microorganisms break down carbohydrates in feed, and release methane as a byproduct. Manure produces both methane and nitrous oxide; the amount of each gas depends on the manure management system, the environmental conditions, and the diet of the animals.[53] Methane emissions from ruminants due to enteric fermentation and manure are responsible for a third of total anthropogenic methane emissions, or approximately 115 million metric tons of methane ($MtCH_4$) compared to about 380 $MtCH_4$ total anthropogenic emissions.[54] Livestock systems also produce carbon dioxide (CO_2) emissions through land-use change, fossil fuels burned in transport, and other processes related to feed production and livestock farming activities.

Livestock system emissions vary regionally and by system type. LMICs contribute to 70% of global non-CO_2 emissions from ruminants (Figure 1).[55] Systems that integrate crops and livestock, or mixed crop-livestock systems, like those common in smallholder farming contexts, produce most of the non-CO_2 (methane and nitrous oxide) emissions from ruminants (61%). Grazing systems account for another 12%, while urban and other systems contribute the rest.[56] The amount of non-CO_2 emissions from different regions are largely driven by animal numbers and the predominant production system (Figure 1). See Box 2 for measurement methods to determine methane emissions in livestock systems.

Figure 1: Greenhouse gas emissions from livestock production vary greatly in different parts of the world due to farming practices as well as animal numbers, type and food product



Credit: Food and Agriculture Organization of the United Nations, results of GLEAM model. *Reproduced from* American Geophysical Union (26 May 2021) CC BY-NC-SA 3.0 IGO Efficient meat and dairy farming needed to curb methane emissions, study finds, AGU Newsroom.

Box 2: Measuring Methane Emissions from Livestock Systems

Methane emission inventories are calculated according to tiers defined by the Intergovernmental Panel on Climate Change (IPCC). Each tier varies in the inputs and level of detail required. The methane calculations throughout this paper follow the IPCC's Tier II approach for enteric fermentation. Tier I is the most simplified methodology for calculating enteric methane emissions, and involves pre-estimated emissions factors and animal numbers by species.[57]

Tier II involves refinement of Tier I data, and includes breed, body weight, feed intake and diet quality estimates. This method aims to collect more information on animal productivity, diet quality, and management to achieve greater methane emissions accuracy. It is sometimes difficult to obtain accurately all the information needed. Tier III involves utilizing/developing country-specific measurements and models to further refine data observations and empirical data, which are subject to peer-review prior to use.

The Tier II approach is dependent on good intake estimates or equations (i.e., how much and what the animals eat per day) and on information about the quality of the diet, to represent methane emissions and methane emission intensity through time. The IPCC Tier I is not useful for calculating mitigation potential because it uses the same emissions factor for all livestock in a given region,[58] and Tier III requires models with sophisticated feed quality data, expert technical knowledge, and data not accessible from most smallholder contexts. For most practitioners, a Tier II approach to emissions estimation, which uses feed intake data and a small number of other inputs like feed quality, is the most appropriate and cost-effective choice.

For more information on IPCC Tier methods for livestock methane calculations, including a decision tree for selecting the most appropriate tier for enteric fermentation calculation, see Chapter 10: Emissions From Livestock and Manure Management in the 2006 IPCC GUIDELINES FOR NATIONAL GREENHOUSE GAS INVENTORIES (Intergovernmental Panel on Climate Change, 2006). Available tools such as the Food and Agriculture Organization's GLEAM can also be used by trained extensionists to estimate greenhouse gas emissions.

B. Meeting Growing Dairy Demand Will Require Productivity Increases for Smallholder Farmers

Smallholder farmers produce one third of food for global consumption on a quarter of gross agricultural area.[59] For the livestock sector, smallholder dairy farms play an important role in global milk production. For example in 2023, India was the third largest producer of cow milk by weight,[60] and 82% of the farmers were considered small or marginal.[61] India produces a substantial amount of animal-sourced products, and is home to the largest number of milk cows worldwide.[62] These systems may be low input, based on crop-residue feeding, and composed of indigenous cattle, which can result in low milk yield compared to productive systems.[63] Beyond the type of production system, factors such as resource constraints, economic disadvantages, technical capacity, social and cultural barriers, and risk averseness may keep smallholder farmers from reaching efficiency levels that allow for increased production from their systems.

Increasing productivity in smallholder systems may help to increase the amount of available food on the market, thereby economically benefiting farmers and alleviating pressures on land. By increasing inputs per unit of land used (i.e., intensifying), the need to deforest for the expansion of agricultural land area may subside.[64] Additionally, implementing a shift to production practices that are more sustainable (e.g., rebalancing of soil inputs) can decrease land-use emissions.[65] There are, however, high uncertainties regarding land-use gains from intensified systems, and sustainable systems are predicated on minimized spillover effects and global dietary changes.[66] Beyond the potential market and environmental benefit of improved productivity, smallholders may also receive benefits to their household (e.g., reduced labor in some cases).[67] At least 1.3 billion people are employed in livestock operations and 600 million poor smallholder farmers receive direct support for their livelihoods from raising livestock.[68] Productivity increases among smallholder farmers that are currently operating below contextually achievable efficiency potentials therefore present an opportunity to enable food security, reduce land pressures, and reduce the most potent greenhouse gases.

2. The Main Pathways to Reduce GHG Emissions from the Livestock Sector

There are four main approaches to reduce methane emissions from livestock:

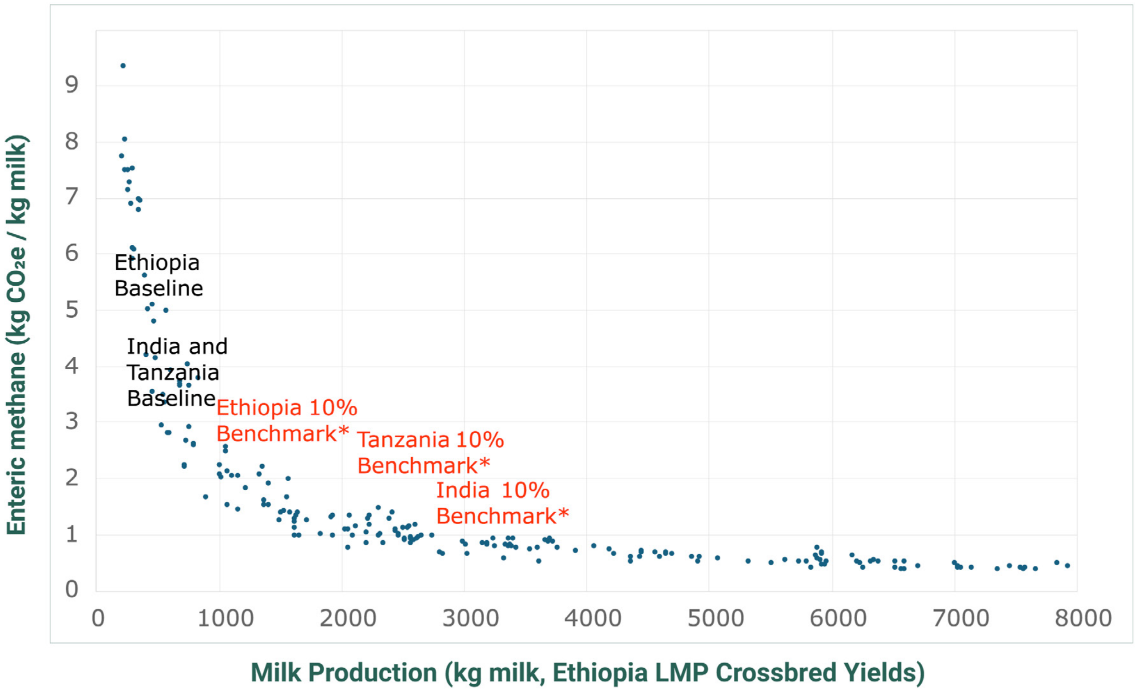
1. Increasing the productivity of meat and dairy production. In low-productivity contexts, this can lead to reduced methane emission intensity (methane emissions per kg of milk or meat produced) and reductions in absolute methane emissions, when paired with reducing the overall number of livestock.
2. Using feed additives or other technology to reduce emissions from enteric fermentation, and maintaining or reducing the number of livestock.
3. Investing in alternative proteins (plant-based, fermentation-derived, and/or cultivated-meat) as a substitute for animal-sourced foods,[69] which may ultimately reduce demand for traditional meat products and aid in reduction of animal numbers.
4. Reducing emissions, by management of manure

Through better land management of land required for livestock, e.g. pastures, it is also possible to sequester carbon from both soil and above-ground sources.

A. Increasing Animal Productivity While Reducing Overall Livestock Numbers

In dairy systems, methane emission intensities per system and country (described in Box 1) can vary between 0 and 10 kg CO_2 eq/kg milk (Figure 2). High methane emission intensities occur largely in LMICs. This is primarily due to low animal productivity across large areas of arid lands, low-quality feeds, lack of sufficient amounts of feed, as well as the use of low-production animals for draft power and to manage household risk in addition to milk production.[70] This is represented in Figure 2 in countries that have low milk production and high methane intensity (e.g., India and Tanzania baseline). In most high-income countries, however, emission intensities are low due to the use of improved and more intensive feeding practices as well as the prevalence of temperate conditions[71] where feed quality tends to be higher.[72]

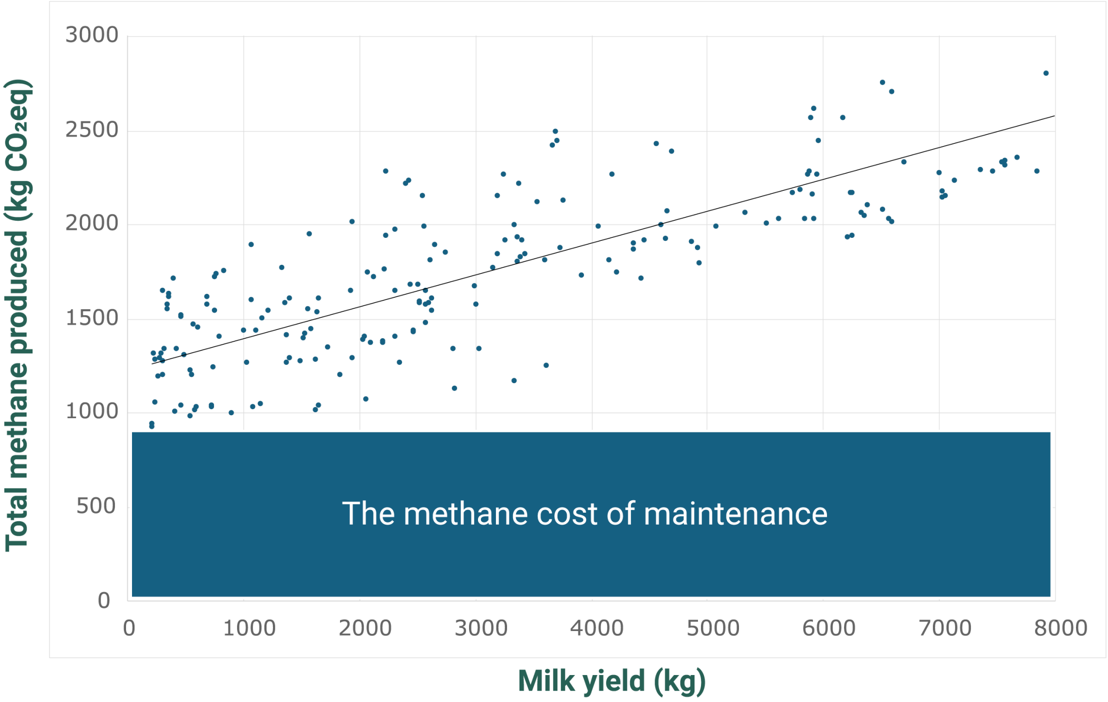
Figure 2: The Relationship Between Milk Production and Methane Emission Intensity



*10% benchmark – emissions intensities of the top 10% of smallholder producers. Methane emissions converted to CO_2-equivalents using 100-year global warming potential (GWP) value of 25 (IPCC AR4). *Data reproduced* from Herrero M., Palmer J., & Mason-D'Croz D. (2019) *Finding the Sweetspot: Trade-offs between productivity increases, structural change the mitigation potential of dairy systems in Ethiopi*a, Commonwealth Scientific and Industrial Research Organization, 24.

In low-producing animals, typically observed in smallholder farmer contexts, the main source of enteric methane is the maintenance requirement of the animals (the blue band in Figure 3), which accounts for most of the emissions. This is like a fixed cost for ruminants; as milk production increases, the maintenance requirement effect is 'diluted'. This is why we typically see a linear increase in total (absolute) methane emissions (Figure 3), but a curvilinear decrease in emissions intensities (Figure 2).

Figure 3: The Relationship Between Total (Absolute) Methane Emissions and Milk Production



Data reproduced from Herrero M., Palmer J., & Mason-D'Croz D. (2019) *Finding the Sweetspot: Trade-offs between productivity increases, structural change the mitigation potential of dairy systems in Ethiopia*, Commonwealth Scientific and Industrial Research Organization, 24 p.

The relationship between the quality and quantity of the diet and methane emissions follows well-established principles: higher quality diets and higher feed intake lead to greater methane production per animal and greater milk yield. Thus, total methane emissions increase linearly with milk production, and variation exists largely due to diet quality (Figure 3). However, methane intensity (methane production per unit of animal product) decreases as the dietary quality improves.[73] Improvements in feed quality is primarily why low methane intensity with increased milk production is observed in Figure 2.

Improved feeding practices and diet formulation have the potential to increase productivity and reduce methane intensity.[74] This has been demonstrated in Kenya, where several feed resources including napier grass (*Pennisetum purpureum*), desmodium (*Desmodium intortum*), mathenge (*Prosopis juliflora*), and calliandra (*Calliandra spp.*)[75] altered milk, manure, and methane production for dairy systems. Studies found improved feeding practices are associated with increased milk production relative to the baseline, and improved feeding practices decrease methane emissions per kilogram of milk relative to the baseline.[76]

To decrease methane intensity and absolute methane emissions simultaneously, increases in productivity—which may be achieved through improved feed quality or improved animal health—must be paired with overall herd size reductions. Tables 1 to 3 demonstrate a simplified example of how intensification and smaller herds may result in decreases in methane emission intensity, as well as in total methane emissions. Table 1 shows three cows of varying milk production, total methane emissions, and methane intensity. In Table 1, Cow 3 has the lowest methane intensity but highest total methane emissions.

Table 1: A Simple Example of Milk Production and Methane Emissions

	Milk Produced (kg/lactation cycle)	**Total Methane (CO_2eq)**	**Methane Intensity (kg CO_2eq/kg milk)**
Cow 1	500	1,200	3–4
Cow 2	1,500	1,500	1–2
Cow 3	3,000	1,750	<1

When you add an additional cow to each original cow on the farm, milk production and total methane double (Table 2), while methane intensity remains the same. Systems with the most milk produced are also the most valuable (Cow 3 in Table 2).

Table 2: Scenario 1—Doubling the Number of Cows

	Cows Needed	**Milk Produced (kg/lactation cycle)**	**Total Methane (CO_2eq)**	**Value of Livestock/ Herd ($)**
Cow 1	2	1,000	2.5 t	500
Cow 2	2	3,000	3 t	700
Cow 3	2	6,000	3.5 t	1,000

Tailoring each farm to produce a certain level of milk (20,000 kg) results in a different number of cows needed, due to the amount of milk produced per cow. The Cow 3 farm has cows that produce the most amount of milk and have a low methane intensity. In Table 1, the Cow 3 farm also produced the highest total methane emissions when compared individually against the other cows. However, scaling to a milk production target (Table 3), cows from Cow 3 farm can reach the target with fewer cows. Fewer cows reduce the level of total methane emissions from a system. Compared to the Cow 3 farm, Cow 1 farm, which comprises cows that are low-producing and have high methane intensities, needs more cows to supply the target milk production; more cows increase total methane emissions. Intensifying a dairy system to meet a milk production target, such as 20,000 kg of milk, can reduce total methane emissions, as exemplified in Table 3, as fewer cows are needed to meet the milk target than in a less intensive system.

Table 3: Scenario 2— Producing a Target Level of Milk Production, for example 20,000 kg of Milk

	Cows Needed	**Milk Produced (kg/lactation cycle)**	**Total Methane (CO_2eq)**	**Value of Livestock/ Herd ($)**
Cow 1	40	20,000	48 t	10,000
Cow 2	13	20,000	20 t	4,500
Cow 3	7	20,000	11.6 t	3,500

B. Novel Feeding Strategies to Reduce Methane Production

Technological change is occurring very rapidly and provides opportunities for transformational change through innovations in the feed sector, digital technologies and robotics, genetics, and many other fields. Several of the emerging options have the potential to disrupt the livestock sector positively in the next decade, if regulatory frameworks, social acceptability, and human health concerns can be adequately addressed (Appendix 1, summarized in Table 4).

Table 4: Emissions Reductions, Risk Management, Applicability, Commercial Availability, and Future Development of Novel Methane Mitigation Practices

Strategy	**Expected CH$_4$ decrease**	**Possible co-benefits**	**Safety and risk management, and licensing challenges**	**Production system applicability**	**Approved for sale**	**Research and Development needs**
Supplementation of lipids	5–20% High confidence	Improved milk/meat production, and fatty acid profiles. Sources are byproducts of the food industry.	Safe for limited intake. Properly formulated diets reduce the effect on products. No licensing issues.	Applicable to all systems, except extensive low-input grazing systems. In total mixed rations or as supplements to grazing.	Market ready.	Low-cost local feeds and byproducts with high lipid contents, and their effects on animals in the Global South, and on meat and milk quality.
Chemical inhibitor (3-NOP)	20–80% (average 30%) High confidence	None expected.	Safe for animals and consumers at correct dose. Possibly a skin irritant and harmful if inhaled by user.[77] Approved in several countries. Manufactured and sold by DSM as Bovaer®.	Currently in total mixed rations. Not for grazing cattle.	3-NOP approved in several countries.[78]	Slow-release formulation to extend use to grazing animals and for non-total mixed ration farms. Long-term effects over multiple lactations.
Bromoform-containing seaweeds	40–98% High confidence	Improved feed conversion efficiency.	Safety not established. Bromoforms are ozone depleting and potential human carcinogens. Possible transfer of inorganic compounds to products. Subject to USDA and FDA approval.	In total mixed rations, but efficacy time period is uncertain.	Early-stage research with a few start-ups working on scaling up and commercialization.	Safety, bromoform content and stability, production, and effects on animal productivity. Aquaculture production. Distribution as feed additive. Long term studies. Bioengineering of crops to incorporate bromoform in small quantities. Slow-release forms for grazing cattle.
Other seaweeds	5–20% High uncertainty	Unknown.	High levels of inorganic compounds may need processing. Safety not determined. Many are already approved for feeding, not related to the methane claim.	Applicable to all systems, except extensive low-input grazing systems.	Early-stage research conducted mainly in high-income coastal countries. At least 5 years from product delivery.	Bioactive and inorganic compounds, production, and effects on animal productivity. Purify or extract the bioactive components.
Essential oils	0–25% Low to medium confidence	Animal productivity.	Low risks. Many are already approved as feed palatability enhancers. May require encapsulation and proper storage. Odor might be a problem.	In total mixed rations; not applicable to extensive grazing systems.	Some products are market ready.	Product formulation. Trials including a long-term trial for each oil. Bioengineering to include some of the anti-methanogenic essential oils into common feeds.
Tannins	5–20% Moderate certainty	Improved nitrogen use efficiency, fatty acid composition, and animal products. Decreased nitrogen excretion, bloat, and intestinal parasites.	High levels can decrease digestibility. Therefore, some of the methane reduction at higher levels can be due to decreased digestibility.	Applicable to all systems.	Some tannin forages are market ready. New extracts in 3–5 years.	Regionally available high-tannin sources. Supplements and extracts using local shrubs/trees. Types of tannins and levels for methane mitigation and animal performance.
Immunization against methanogens	10–15%. High uncertainty	None.	Safety unknown. Veterinary drug regulatory approval needed.	Expected to have broad applicability globally.	In the experimental stage.	Demonstrate in live animals. Antigens across diverse rumen methanogens. Persistence of immune responses.

Adapted from Reisinger A., Clark H., Cowie A. L., Emmet-Booth J., Gonzalez Fischer C., Herrero M., Howden M., & Leahy S. (2021) *How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals?*, Philos. Trans. R. Soc. A 379(2210): 20200452.

Superfeeds, like algae or grasses with high oil content (which have more metabolizable energy compared to typical fodder),[79] are currently the subject of significant methane-mitigation research. The most promising alga-based feed is a type of red alga called *Asparagopsis taxiformis*. Research demonstrates that this additive to cattle diet may decrease methane emission intensity by up to 98%, although results are highly variable.[80] This would be useful for confined animals in smallholder systems, feedlots, or dairy operations. Technically, assuming a constant growth of 25–50 million hectares of cultivation of algae up to 2060, algae systems used as feedstock and biomass could potentially replace 2 billion hectares of grasslands and croplands.[81] This would lead to significant mitigation as some of the freed land could also be used for afforestation (planting a forest where there was previously not one) and rewilding (restoring a forest to its natural, uncultivated state), thus also promoting negative emissions technologies. While this is only a demonstration of technical potential and does not assess the economics to enable this, it shows the boundaries of what could be possible when the right sets of incentives are developed. In some Global North countries, animal products raised with algae feed supplements are already available for purchase.[82]

Engineers have also created methods to produce high-quality microbial proteins by fermenting sewage with a source of CO_2 and energy.[83] After cleaning, drying, and pasteurizing the material, this is transformed into a powder that can be used as an ingredient by the feed industry to replace protein sources like soybeans. Under appropriate production pathways and aligned socioeconomic development conditions, microbial proteins can replace between 10% and 19% of conventional animal-feed protein demand by 2050.[84] This demand would otherwise be met by vast areas of arable land, including one-third of cereal-producing croplands that are used to produce proteins that are fed to animals instead of directly meeting human nutritional needs.[85] This research assumes that microbial proteins would replace cereals, but would not replace feeds that incorporate crop residues, forage crops, pasture, molasses, and other feed items.[86] Successful replacement could lead to decreases in global cropland area (6%), global cropland losses of nitrogen (8%), and agricultural greenhouse gas emissions (7%).[87]

Another notable example, already in the market but with potential for increased commercialization, is the compound 3-nitrooxypropanol (3-NOP, manufactured and sold by DSM as Bovaer®), which can decrease methane by up to 55% when incorporated in diets for ruminants.[88] Several countries have approved the sale of Bovaer®,[89] but the supplement still faces regulatory hurdles.[90] The EU granted regulatory approval of Bovaer® in February 2022 and has planned large-scale pilot programs.[91] These novel feeds could potentially mitigate large amounts of methane, but the land footprint of ruminants, and the CO_2 and nitrous oxide emissions from ruminants will remain. Focusing on productivity is an additional lever that could alleviate the land pressures while also mitigating methane and nitrous oxide emissions.

In cases where milk yields have increased beyond the range in which improvement in productivity can have an impact on emission intensity, these new technologies (Table 4) can reduce the methane emissions produced by enteric fermentation.[92] However, while these options are promising, there are still significant barriers to adoption and implementation of them in LMIC countries (Table 4), with cost being the most important impediment. As a result, these novel anti-methanogenic compounds are not yet available in smallholder contexts. New production methods can increase supply and, as the private industry gets more involved, these feeds might become more available and less expensive, thus opening additional avenues for improvement in LMICs.

C. Investment and Growth in Alternative Protein Sources

Offering more protein options in markets that can afford to do so could work in tandem with reducing demand for livestock products, thereby reducing herd sizes and the impact of methane from livestock systems. Research suggests that replacing half of traditional animal proteins (e.g., red meat) with alternatives by 2050 can decrease greenhouse gas emissions (methane, nitrous oxide, carbon dioxide) by 31%.[93] A contraction in meat consumption in high-income countries, which consume red meat beyond health recommendations, can additionally be beneficial to human health, mainly by reducing the risk of heart disease, obesity, and colorectal cancer, and associated mortality.[94] Additionally, alternative proteins do not contribute to the presence of antibiotic-resistant microorganisms as they do not require antibiotics in their production, which is a significant health concern with animal proteins.[95] While markets for alternative proteins are developing,[96] they have yet to reach LMIC markets and they still face regulatory and R&D hurdles in high-income country markets.[97] Additionally, regional differences in dairy consumption and protein-deficiency rates must be considered to ensure a more equitable and sustainable approach to shifting diet composition.

D. Managing Manure to Emit Less Methane and Nitrous Oxide

Manure methane is generated according to the way that the manure is stored. Leaving manure in wet, anaerobic conditions (low to no-oxygen) promotes growth of microbes that produce methane. Several strategies (e.g., methane-inhibiting additives, improved manure management such as separating solids from sludge, and capture and use of manure with anaerobic digestion technology), which vary in technical complexity, may reduce methane emissions from manure. These manure management strategies are usually employed to reduce nitrous oxide, with a small benefit to reductions in methane.

Additives that inhibit methanogenesis: Additives that enhance organic matter degradation, including biochar (black carbon produced from pyrolyzing biomass), acids, straw, and gypsum-like compounds, may reduce methane emissions when added to manure.[98] Some of these additives have been shown to reduce methane emissions by 80%,[99] but the suitable additive and application type will vary per farm.

Anaerobic digestion technology: Another option to reduce methane emissions from manure is through anaerobic digestion, a technology that converts organic waste to two products: biogas and digestate, which can be used as a fertilizer.[100] Using the digestate could reduce fertilizer requirements, thereby reducing emissions of nitrous oxide, which is another potent greenhouse gas. This technology, though promising, must be assessed per farm.[101] Several factors, including technical understanding, input magnitude, storage capacity, financial constraints, and ability to use biogas and digestate products, can all work to encourage or discourage the use of this technology on a farm.

Alternative manure management strategies to reduce methane production: Managing manure without technological intervention is another avenue to reduce methane emissions. Some studies find that separating manure sludge into solid and liquid components and/or removing the manure from barns soon after formation could inhibit the production of methane.[102]

In smallholder contexts, the appropriate strategy would depend on the farm characteristics, such as available tools, available labor, how the animal waste is processed, access to methane-inhibiting additives, and access to gas infrastructure in the case of anaerobic digesters.[103] While some of these strategies are already available in smallholder contexts, the overall benefit of reducing methane emissions from manure is smaller than mitigating enteric fermentation emissions.

3. Approaches to Increasing Productivity and Monitoring Interventions in Smallholder Contexts

Increasing animal productivity using improved feed and feeding strategies has great potential for achieving reduced yield gaps and reduced methane emissions – see Box 3 for examples from Precision Development's dairy programs across different countries. Smallholder farming systems in sub-Saharan Africa and South Asia are known to have substantial yield gaps[104] and therefore to have a large potential to increase food production.[105] The baseline production of dairy products in developing countries such as Tanzania, Ethiopia, and India can be very low with high methane emission intensities (see Figure 2).[106] Part of this yield gap can be closed by management decisions including more precise matching of inputs and feeding practices to increase productivity while decreasing methane emissions (technical efficiency improvement),[107] and by the adoption of more productive technologies such as improved animal breeds.

Currently, adoption of better feeding practices, like improved forages, have shown low adoption rates. Previous studies found adoption of dual-purpose crops (planting crops like grain, which is intended to be grazed on by livestock before the crop is harvested),[108] agroforestry practices, and improved pastures had adoption rates in the order of 15–25% of farmers in selected LMIC regions, over a 10–15-year horizon.[109] This adoption rate may be low in part due to constraints such as lack of information, risk aversion, lack of access to input and output markets, lack of financial incentives, and competition for land and labour with other activities.[110] Increasing adoption rates will require significant public and private investment and institutional change, not only to increase farmer adoption, but also to reduce long adoption lag times.

Altering diet or herd size at the smallholder level is not without complications. Farmers receive advice cost-effectively and at scale from digital agricultural advisory services, which aim to provide farmers with information, data, and networks that can improve their farm operations. A growing literature on mobile phone-based agricultural information services underscores the potential of information and communication technology (ICT) to promote, cost-effectively, modern agricultural practices.[111] Well-designed messages can improve farmers' knowledge and comprehension as well as change farmers' behaviour. A meta-analysis of six studies in Kenya and Rwanda found that, on average, farmers who received messages about agricultural lime were more likely to adopt the input than farmers who did not.[112] In Gujarat, India, when PxD supplemented the state's Soil Health Cards with different types of digital extension, farmers who also received an audio supplement comprehended the recommendations 37 percentage points higher than those who did not.[113] Digital agricultural advisory services are, by the nature of ICT, easily scalable and cost-effective. For example, Precision Development's program data on their digital agricultural advisory services show that per user costs when the service is established are as low as $2/user/year. Mobile phone ownership, including ownership of smartphones, is expected to increase in coming years. As of 2023, 61% of women and 75% of men in LIMICs use mobile internet.[114]

Other tools that support smallholder dairy farming systems, such as MoooFarm, do not emphasize strategies to reduce methane via productivity improvements.[115] Despite the growth of decision support tools that provide advice about diet changes or herd size reductions for dairy farmers,[116] more progress must be made to determine how these tools may be applicable and accessible to LMICs to achieve methane emission reductions.

Box 3: Estimating Baseline Methane Intensity: A Case Study of PxD's Dairy Farmers in Kenya, Ethiopia, and Pakistan

Successfully leveraging animal productivity increases for methane mitigation requires a robust understanding of the local livestock environment to inform program design; baseline emissions from existing farmer practices are particularly important. Baseline emission data allows for the evidence-based identification of where productivity gains can be made, and of the feasible and effective levers for productivity gains in a specific context.

A commonly used Tier II model for an emissions estimate (described in Box 2) focuses on methane intensity,[117] which is a function of methane emissions per kg of milk produced. Inputs needed for emissions estimations using this approach in dairy farming include:

- Cow productivity, in kg of milk per day (by animal group and season)
- Cow body weight, in kg (by animal group and season)
- Feed quality based on dry matter digestibility (DMD), using a qualitative assessment (benchmarks: poor < 64% DMD, moderate = 64–70% DMD, good > 70% DMD) or identifying feed-specific DMDs (by animal group and season)

Methane intensity of dairy production per cow can then be calculated by estimating feed intake, using cow body-weight and feed quality, and multiplying feed intake by the established methane to feed intake ratio from Charmley *et al*. (2015).

- Feed intake, as dry matter intake (DMI)[118], is calculated as follows using cow body weights and the DMD of cow feed, which is a percentage and can be found in feed libraries which are extensive in East Africa and India (e.g., sub-Saharan Africa feeds composition database):
  DMI = 0.0107 x body weight / (1–DMD)
- For each animal group and season, the calculation of methane intensity is the following:
  Methane emissions per (season) = (feed intake in kg per day) x 20 g CH_4 per kg food x season days

Precision Development (PxD) utilized this Tier II approach to estimate baseline methane intensities for the dairy farmers it works with across three different contexts:

- Kenya: In Kenya, PxD engages with dairy farmers by working closely with dairy cooperatives to provide value-added services, including an asset collateralized loan mechanism for water tanks to reduce dairy farmers' vulnerability to water shortages.
- Ethiopia: In Ethiopia, PxD engages with dairy farmers through direct-to-farmer mobile-phone-based advisory services as part of a wider donor-funded initiative to strengthen the country's dairy sector.
- Pakistan: In Pakistan, PxD engaged with dairy farmers as part of a larger set of interventions funded by the International Fund for Agricultural Development (IFAD), and delivered

by PxD, to assist smallholder farmers, particularly women farmers, as they navigated escalated livelihoods-related challenges associated with the COVID-19 pandemic.

PxD collected the data required for the described Tier II approach through a combination of digital and in-person farmer surveys, rather than directly measuring inputs. Recall bias in surveys means inputs like feed intake or productivity may intrinsically contain some error. PxD used standard data cleaning protocols to address anomalies arising from recall bias and other data quality issues (e.g., by winsorizing outliers).

In all three contexts, methane intensity, Figure 4, and total methane, Figure 5, follow the same relationship with milk production as observed in Figure 2 and Figure 3, where low-producing systems have high methane intensities. This highlights the role that improving productivity through higher-quality diets can play in reducing methane emissions from dairy production, especially in LMICs in tropical climates.[119]

Figure 4 – Relationship between Methane Intensity and Milk Production in PxD Dairy Programs

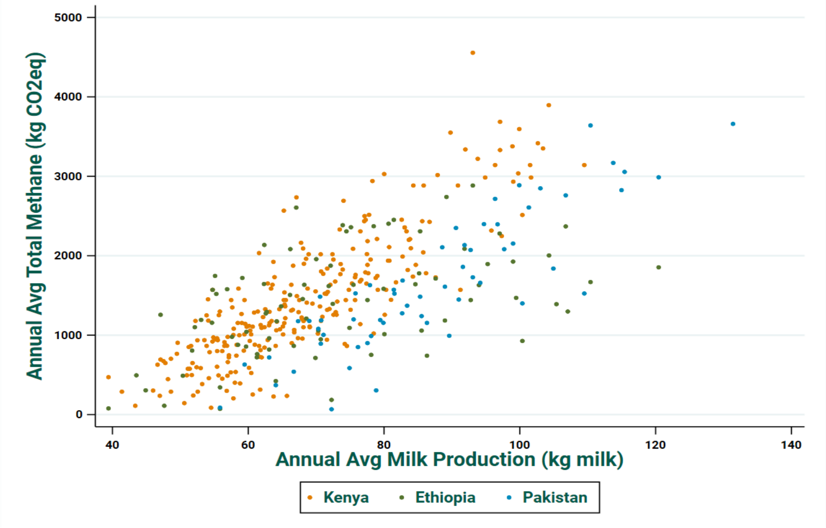
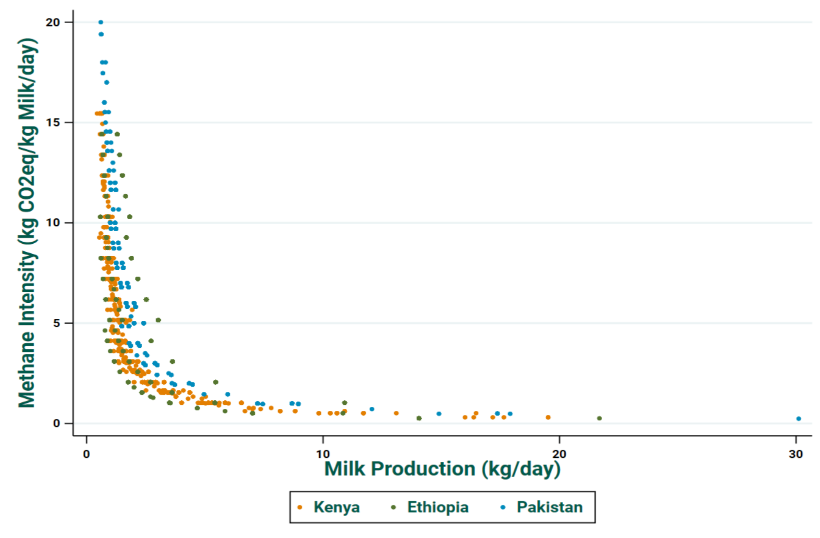


Figure 5 – Relationship between Total Methane and Milk Production in PxD Dairy Programs



We acknowledge the work of PxD's Kenya, Ethiopia, and Pakistan country teams in collecting and analyzing this data, especially Julia Eigner and Sajwaar Khalid.

4. Intentionally Achieving Sustainable Intensification

Regulating intensification to be truly sustainable in the smallholder context—to operate within the limits of production growth, protect biodiversity and ecosystems services, and attain net or near-net reductions in emissions—remains a critical challenge. The concept of sustainable intensification may appear as a win-win strategy to increase resource-use efficiencies, but these changes may not always bring financial or general livelihood benefit to the farmer.[120] From a livestock perspective, most well-managed intensification practices in the past have also led to improved profitability (e.g., pasture intensification and supplementation in the tropics has significantly improved milk and meat production). As a result, farmers have often increased the size of the operation to incorporate more animals, resulting in more land-use changes, to further the economic returns. In some cases, this growth has led to increased environmental problems: more deforestation, more land degradation, more temperature forcing, more greenhouse gas emissions, and other resource-use intensification.[121] To avoid further environmental degradation but maintain production increases, the most appropriate strategy for intensification requires having fewer animals, but of higher productivity.[122] This would imply reversing the observed trend of increasing ruminant numbers (in some regions) as the main source of production growth, as happened earlier in OECD countries.[123]

A. Sustainable Intensification Strategies Depend on the Region

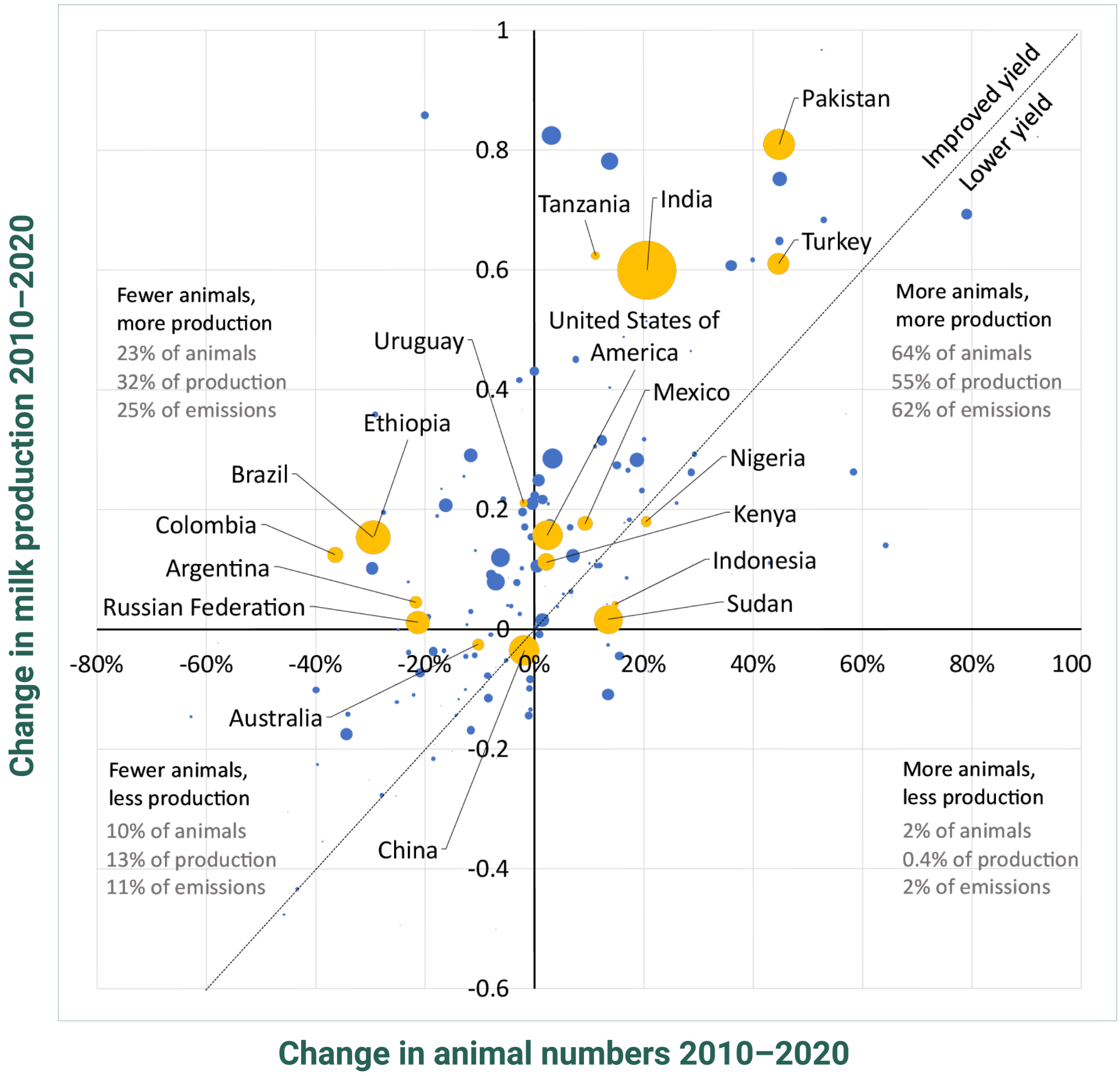
Sustainable intensification in practice can be observed through milk production and animal population records. A 2023 paper by Gonzalez-Fischer and Herrero currently under review[124] gives the following insights into sustainable intensification in practice:

> Over the last 10 years, the number of global milking animals has remained fairly constant, while total milk production increased by ~20%. Average national milk yields have increased in most countries, with a global increase of 17%. However, there is variability regarding income level and region. Milk production increased by 15%, 10%, 48%, and 13% in high-, upper middle-, lower middle-, and low-income countries, respectively. With animal numbers, we observed a change in the number of cows from high- and upper middle-income countries (reduction of 4% and 12%) and lower middle- and low-income countries (increases of 17% and 3%). This results in average yield increases of 20–27% in the three higher-income categories, but just 9% in low-income countries. Likewise, although most of the world regions increased their average yield (between 14–42%), East and Southeast Asia saw yields reduced by 8%, and sub-Saharan Africa showed very little change (a slight reduction of 1%).

Beyond regional differences, there is high variability in the evolution of the dairy sector in different countries. Figure 6 shows the relative change in milk production and milking animal numbers between 2010 and 2020 for each country. Each quadrant of the plot represents a distinct trajectory of the dairy sector, with the upper left representing possible cases of sustainable intensification, with increased output and fewer animals (animals can be a proxy for enteric fermentation emissions). The upper right quadrant shows the more common situation in which both output and animal numbers increased, which would increase absolute enteric methane emissions. Above the diagonal are cases with increased productivity, where the increase in production outgrew the increase in animal numbers. For example, while both Brazil and India have increased production and improved their average yields, India has done so by increasing the number of animals, which increased the methane emissions from enteric fermentation of those milking animals by 27%, while Brazil has reduced animals numbers, and thus reduced methane emissions from enteric fermentation emissions by 23% (note that this reflects the changes in the enteric fermentation from the milking animals only, and it includes neither changes in other sources nor the impact of management changes). On the other hand, both Sudan and Mexico saw an increase of both animal numbers and production. However, Mexico increased its yield, whereas Sudan saw a decrease.

Figure 6: Changes in Milk Production and Dairy Animal Numbers Between 2010–2020 by Country

Bubble size represents the share of global methane emissions in 2020; the countries in yellow represent 60% of global emissions and animals, and 55% of milk production.



Data reproduced from Gonzalez-Fischer C. & Herrero M. (2023) Net greenhouse gas mitigation in the livestock sector requires a reduction in animal numbers (under review).

There are still many opportunities to reduce emission intensity by increasing productivity (in particular, in low-income countries), and these differ by production system. Examples of such opportunities include the transition of livestock production systems from extensive rangeland systems to mixed crop-livestock systems,[125] and through improving livestock management within the existing systems.[126] Key strategies to sustainably intensify livestock systems include the provision of better quality feed (e.g., supplemented with legumes and crop byproducts; improved pastures;[127] in cut-and-carry systems; through strategic use of grain supplements[128]) and optimization of grazing management[129] (e.g., forage conservation like dry season grazing reserves, hay making, and silage production), along with better breeding, fertility and health interventions.[130]

B. Implementing Sustainable Intensification Practices Must Be Balanced with Farmer Needs and Environmental Considerations

There are adaptability issues and side-effects that must be considered when implementing these strategies. For example, breeding practices from temperate regions may not adapt well to the warm conditions in Africa. A shift in productivity might involve an increase in the consumption of grain-based feed, which can lead to trade-offs with food for human consumption.[131] In semi-arid regions where increasing crop production for feeding livestock is impossible due to water limitations (e.g., central Asia), improving grazing management to increase productivity should be prioritized as a sustainable solution, rather than moving to industrialized systems (i.e., landless livestock systems with livestock fed by grain-based feed and/or high-quality fodder).[132] Improving livestock production efficiency should always complement the natural circumstances in the region, and the optimal strategy should consider water pollution through nutrient runoff, and relevant sustainability goals such as biodiversity. Most importantly, implications for livelihoods and resilience to climate change impacts must be considered.

Any mitigation from improvements in emission intensity can easily be overturned by increases in animal numbers (as demonstrated in Tables 1 to 3). Making changes to increase production will vary depending on local context, and will have different total environmental impacts. In this review, we considered emissions from enteric fermentation, but some of the solutions analyzed here could have knock-on effects for other sources of emissions (e.g., land-use change and fertilizer use), and even other environmental dimensions (e.g., water use, nutrient balances, or air quality).

5. Recommendations

Tackling methane emissions in smallholder dairy contexts presents a huge opportunity to ensure food security, reduce the environmental burden of livestock operations, and improve the livelihood of dairy farmers. Significant resources are needed to overcome barriers such as: low farmer understanding and low adoption of new strategies; finding finance for these strategies to reach smallholder farmers, with opportunities to scale up; and potential adverse environmental impacts. In this section, we list several recommendations to achieve this complex, yet worthwhile, initiative.

Increase animal productivity and reduce herd size. Increasing milk production in dairy cattle reduces methane emission intensity per liter of milk (Figure 2) but increases overall methane emissions (Figure 3). Cattle that yield more product can allow farms to reach a productivity target with fewer animals than farms with lower productivity, thus reducing the required herd size. If farmers reduced their herd size due to productivity increases, they would reduce absolute methane emissions.

Animal productivity improvements may be achieved through modified feeding strategies incorporating crop residues, cut-and-carry grass, and legume-based feeding, and/or strategic supplementation. Health improvement strategies, such as improved animal health management and husbandry, will additionally support modest gains in animal productivity. Strategies must align with the needs of indigenous cattle breeds, which form most of the smallholder herds in our observed geographies. To support the transition to lower-methane-emitting practices, tools, which map out feeding types based on environment, farm type, local context, weather, etc., should be created for smallholder farmers. Additionally, these strategies must be low cost to encourage uptake in the smallholder context. Creating value chains for fodder in tandem with higher-quality feeds is an avenue for reducing methane emissions and increasing dairy productivity.

Strategies that focus on the future of herds, such as cross-breeding schemes, may also increase animal productivity and lower the emission intensity of dairy production. Investing in cross-breeding schemes as part of other technological advancements (e.g., novel feeds, vaccines, artificial insemination) can support methane reductions in dairy operations. While these strategies are worth supporting, they will take time to be implemented and may not be accessible in the smallholder context.[133] Prioritizing the productivity of existing animals is fundamental to offering solutions that could have immediate benefits.

Tailor metrics and markets to incentivize increasing production while lowering methane intensity and absolute methane emissions. Currently, metrics and markets are not well aligned with reducing methane emissions from dairy operations. There are many different metrics that may bias practices that can increase absolute methane emissions (Box 1), and markets may encounter a similar story. Reforming metrics and targets to achieve low methane intensity and low absolute methane emissions from production systems (e.g., tons of meat and kilograms of milk with production and emission targets) can alter production practices to emit less methane. Additionally, providing incentives for sustainable production increases in markets (e.g., dairy cold chains, milk collection hubs, processing plants) can increase access to these strategies and reduce the financial burden on farmers. Successful examples exist in East Africa of ways to systematically provide higher volumes of safe milk for consumers.

Provide technical support to farmers and extensionists to increase uptake of efficient production strategies (Box 4). Achieving climate outcomes at scale in smallholder farming contexts in LMICs requires a deep understanding of farmer incentives and needs, existing markets and the states of market access, and the evidence behind potential interventions.

Box 4: Precision Development's Approach to Technical Support for Smallholder Farmers

Precision Development's work building agricultural information systems for smallholder famers, and providing other value-added services, is informed by principles as well as a commitment to farmer-led program design. Operationalization examples of these principles at PxD include:

- At every stage of service design and delivery, we generate insights on how to serve our users better, and rigorously test these insights. At scale, these systems allow us to gather large amounts of direct feedback from users in order to continuously improve our performance.
- We conduct A/B testing—comparing two or more service design options to assess which is preferred or more effective—to inform rapid upgrades to our content and service delivery. Drawing on insights from our program data, external behavioral science evidence, and best practices among peer organizations, to design these tests, we iterate improvements to user experience and deliver more appropriate, accessible and customized information.
- We deploy human-centered design practices to continuously improve our understanding of our users, and to design products and interfaces that meet our users where they are—including design for low-literacy, technology-constrained, very low-income users.
- We use experiments and trials to systematically understand the impact of our services and feed this information back into our model to refine it over time.
- We engage with, learn from, and contribute to leading academic and policy research in the behavioral sciences, economics, and other social sciences.

Increasing the uptake of strategies that reduce methane emissions in smallholder dairy contexts will additionally require the training of extensionists to estimate greenhouse gas emissions. This will help to establish reasonable baselines of productivity and emissions for improving the monitoring of GHG emissions and mitigation practices. Further training on food safety at the smallholder level can support the achievement of health goals, and ensure that high quality milk reaches consumers.

Launch pilot projects to test interventions for overcoming barriers. Pilot projects offer relevant information about the applicability of certain strategies. Intentionally planning projects that aim to improve productivity and livelihoods, while reducing overall emissions, must be prioritized to improve the environmental impacts of livestock systems. Projects that do not achieve external objectives (e.g., food security, human welfare) beyond methane emission reductions are not sustainable and are unlikely to be scaled. Following the project implementation and achievement of successful outcomes, novel instrument payments for environmental performance must be designed to encourage further adoption of sustainable practices.

Despite a brief stabilization of methane emissions about three decades ago, methane emissions have continued to rise quickly year on year.[134] A large proportion of these emissions are from agriculture, particularly the raising of livestock. It is critical to reduce these livestock emissions to meet global climate goals. A key part of these reduction strategies is targeting interventions in regions where methane intensities are highest, primarily smallholder livestock systems in LMICs. Sustainably intensifying production in these systems will not only improve GHG emission from the livestock sector, but also help to meet the increasing demand for livestock products (e.g., dairy) and contribute to livelihood improvements.

Appendix 1: Emissions Reductions, Risk Management, Applicability, Commercial Availability, and Barriers to Adoption of Novel Methane Mitigation Practices

Supplementation of lipids Adding oils, oilseeds or other high-fat feeds to the diet. The lipids decrease methane, and the additional digestible energy can increase animal production.	
Efficacy (expected CH_4 decrease) and level of confidence	5–20% decrease in methane depending on the level of fat supplementation and diet. High confidence. A number of meta-analyses are published. There are differences between lipid sources, and oils vs. oilseeds, but these differences are relatively small.
Co-benefits	May improve milk/meat production and fatty acid profiles. Many lipid feed sources are byproducts and waste from the human food industry. Can increase animal production if dry matter intake is not decreased.
Safety and risk management, and licensing challenges	Safe, but the total lipid content of diet must be limited to 4–6% of dry matter to limit the negative effects on intake and digestibility, especially for high forage diets. Milk fat depression and “soft” butter can occur if diets are not formulated properly. No licensing issues.
Production system applicability	Applicable to all systems, except extensive low-input grazing systems. Can be incorporated into total mixed rations or offered as supplements to grazing cattle.
Approved for sale in specific markets	Market ready.
Barriers to adoption on-farm, cost effectiveness, and development needs	Can be costly. Lipids are already used in many dairy diets in North America and the EU as a source of energy. Substantial research is already published for intensive systems, but research in low- to moderate-income countries is scarce. Opportunities for lipid inclusion are higher in less developed production systems. Need to identify low-cost local feeds and byproducts that have high lipid content, and their effects on animals in the Global South (total cost $2–5 million). This requires feed analysis and incorporation of results into feed formulation software. Need more information about the effects on meat and milk quality.
Chemical inhibitor 3-Nitrooxypropanol (3-NOP)	
Efficacy (expected CH_4 decrease) and level of confidence	Average efficacy of 30% (ranges from 20 to 80%), which is dose-dependent and inversely affected by fiber content of the diet. At the same dose, responses are greater for dairy vs. beef cattle. High confidence with over 50 published papers.
Co-benefits	None expected. Minimal effects on animal productivity and manure.
Safety and risk management, and licensing challenges	Correct dosages are necessary. Regulatory approval is needed (3-NOP is approved in several countries). There is no carry-over in meat and milk. No safety risks for animals and consumers if administered at appropriate dosage; can be a skin and eye irritant and harmful if inhaled by user.[135] 3-NOP is manufactured and sold by DSM as Bovaer®.
Production system applicability	The current form is for incorporation into total mixed rations. Not applicable to grazing cattle.
Approved for sale in specific markets	3-NOP is approved in several countries.[136] Dossiers have been submitted to various countries by DSM. Regulatory approval in most jurisdictions requires an extensive efficacy and safety dossier, as inhibitors are considered “drugs” because they change animal metabolism.
Barriers to adoption on-farm, cost effectiveness, and development needs	Cost at farm level unknown; without co-benefits 3-NOP will increase the cost of feeding. Need to develop a slow-release formulation to extend use to grazing animals and for non-total mixed ration farms (total cost $5–10 million). More information is needed about the long-term effects over multiple lactations (methane and animal production/health) and the potential adaptation of the rumen ($2–5 million). Research is controlled and mainly funded or co-funded by DSM, as they control the supply of the product.
Bromoform-containing seaweeds (Asparagopsis sp.) About 5–8 experiments have been conducted so far with all showing consistent results in the high potential to reduce emissions.	
Efficacy (expected CH_4 decrease) and level of confidence	Efficacy depends on basal diet and dose but in general it ranges from 40 to 98%. There is a high level of confidence in the efficacy shown. Life cycle assessments are needed to provide information on the net methane-emission reduction, taking production and transport into consideration.

Co-benefits	A couple of small experiments have shown that there is an improvement in feed conversion efficiency, i.e., animals consume less feed but gain some weight compared with those in the control group.
Safety and risk management, and licensing challenges	Safety risks need to be established; bromoforms are ozone depleting and potential human carcinogens. May need processing as there could be high levels of inorganic compounds transferred to products. Subject to USDA approval of feed seaweed (currently approved for trials), and FDA approval for methane mitigation and efficacy.
Production system applicability	Suitable for incorporation into total mixed rations. How long the efficacy lasts is unknown, so more work is needed in this area. Efficacy lasting up to a week will broaden the range of applicability.
Approved for sale in specific markets	There is early-stage research with a few start-ups working on scaling up and commercialization.
Barriers to adoption on-farm, cost effectiveness, and development needs	Need information on safety, bromoform content and stability, product production, and effects on animal productivity. Cost effectiveness is unknown, but products potentially can be produced in aquaculture settings and distributed as feed additives. More experiments are needed, including long term studies of either one or two lactations, and a clinical trial (total cost $5–10 million). Developing a product and getting it to a commercial setting requires further investment, which start-ups are taking control of. Currently, research is underfunded so commercialization is over 5 years away. A long-term plan would be to try to incorporate bromoform in small quantities using bioengineered crops, and slow-release forms for grazing cattle.
Other seaweeds Seaweeds, other than *Asparagopsis*, that inhibit methanogenesis due to the presence of specific bioactive components.	
Efficacy (expected CH_4 decrease), and level of confidence	Decrease in methane of 5 to 20% but life cycle assessments are needed. High uncertainty as there are few published papers so far, but this area is expanding in coastal countries.
Co-benefits	Unknown, but many of these seaweeds are highly digestible and may increase animal productivity.
Safety and risk management, and licensing challenges	Some seaweeds may contain high levels of inorganic compounds (e.g., iodine) and may need processing. Will need to determine safety, including residues, and off-flavors in meat and milk. Approval by government agencies may be needed for the methane-reduction claim, but many of these seaweeds are already approved for feeding, so regulatory issues may be fewer than for *Asparagopsis*.
Production system applicability	Applicable to all systems, except extensive low-input grazing systems.
Approved for sale in specific markets	Early-stage research is being conducted, mainly in high-income coastal countries. At least 5 years from product delivery.
Barriers to adoption on-farm, cost effectiveness, and development needs	Need research on bioactive and inorganic compounds, production, and effects on animal productivity (total cost $5 million). May need to purify or extract the bioactive components to minimize shipping costs and inorganic contaminants. Adoption will depend on cost:benefit analysis and regional availability. Currently, research is underfunded so commercialization is over 5 years away.
Essential oils Naturally occurring chemical compounds extracted from plants or synthesized chemically. Products, e.g., Agolin, are usually blends of essential oils. Mootral is synthesized from natural products including garlic and flavonoid-containing-citrus extracts and has demonstrated anti-methanogenic properties. Tropical-grown lemongrass has also being shown to reduce emissions.	
Efficacy (expected CH_4 decrease), and level of confidence	0 to 25% efficacy. Low to medium confidence due to the lack of published animal studies so far. However, this area is expanding.
Co-benefits	There is potential to increase animal productivity. There is evidence for at least Agolin to improve milk production.
Safety and risk management, and licensing challenges	Low risk. Many are already approved as feed palatability enhancers. Essential oil products can be unstable and require encapsulation and proper storage. Odor might be a problem in some cases (Mootral has a heavy garlic smell to it).
Production system applicability	Suitable for incorporation into total mixed rations; not applicable to extensive grazing systems.
Approved for sale in specific markets	Some products (Mootral, Agolin) are market-ready for methane reduction, but based on limited research. Agolin is already being sold to increase milk production; but methane mitigation is less than 10%, based on a few studies. Mootral shows up to 23% reduction in one study, but this needs substantiation in science-based publications.

Barriers to adoption on-farm, cost effectiveness, and development needs	Research to date has focused on animal productivity although some products are developed for methane abatement specifically. Research is needed on optimum product formulation for methane mitigation. Further trials are needed for oil-based additives ($3–4 million), with at least one long-term trial for each ($1 million). Most are based on natural products which facilitates USDA approval of them as feed additives, but FDA approval is still required if methane reduction is to be claimed. A long-term plan is to include some of the anti-methanogenic essential oils into common feeds through bioengineering technology.
Tannins Condensed and hydrolysable tannins contained in some plants (forage, shrubs, and leaves and bark of trees). Can also be prepared as extracts.	
Efficacy (expected CH_4 decrease) and level of confidence	5 to 20% efficacy. Moderate certainty with reduction being dose-dependent.
Co-benefits	Can improve nitrogen-use efficiency and decrease nitrogen excretion. Can prevent bloat, control intestinal parasites, and improve the fatty acid composition, oxidative stability, and sensory qualities of meat and milk.
Safety and risk management and licensing challenges	High levels (> 3% of dietary dry matter) can decrease digestibility. Therefore, some of the methane reduction at higher levels can be due to decreased digestibility.
Production system applicability	Applicable to all systems. Tannin-containing forage mainly for pastoral systems; extracts for total mixed ration systems.
Approved for sale in specific markets	Some tannin forages are market ready. New extracts are expected in 3–5 years.
Barriers to adoption on-farm, cost effectiveness and development needs	Much research has been done in vitro, with positive results. Need more animal research using regionally available high-tannin sources ($5–10 million). Potential exists to develop supplements and extracts based on using local shrubs/trees ($3–4 million). More work is needed to characterize the effects of the types and amounts of tannins on methane mitigation and animal performance ($2 million).
Immunization against methanogens Growth and methane production of a pure culture of a methanogen were inhibited by a vaccine, but ruminants contain numerous different species of methanogens.	
Efficacy (expected CH_4 decrease) and level of confidence	10 to 15% efficacy. High uncertainty, as the research is developmental.
Co-benefits	None.
Safety and risk management and licensing challenges	Safety concerns are unknown, but vaccines are likely to be low risk, given that antibodies naturally exist in animal tissues. Vaccines are veterinary drugs so must go through appropriate regulatory approval processes.
Production system applicability	Expected to have broad applicability globally. This is especially attractive for extensive systems if the requirement is one or two doses of the vaccine.
Approved for sale in specific markets	Still at the experimental stage and may take over 5 years to reach the market.
Barriers to adoption on-farm, cost effectiveness and development needs	Not yet demonstrated in live animals and still at a proof-of-concept stage. Vaccines may lack a broad-spectrum effect on rumen methanogenic communities. Research is needed to select appropriate antigens present across diverse rumen methanogens; and to assess both the antigen efficacy against cultivable rumen methanogens, and the persistence of immune responses across ruminant populations. Total cost to develop vaccines is upwards of $10 million. May be cost effective as the production of vaccines (if given one or two shots) could potentially be covered through incentives. So far mainly driven by New Zealand. Long term plan depends on in vivo experimental results.
Adapted from Reisinger A., Clark H., Cowie A. L., Emmet-Booth J., Gonzalez Fischer C., Herrero M., Howden M., & Leahy S. (2021) How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals?, Philos. Trans. R. Soc. A 379(2210): 20200452.	

References

1 Khanna K. (6 May 2022) *How Methanogenic Archaea Contribute to Climate Change*, American Society for Microbiology ("Methanogenesis or methane production relies on substrates like CO_2/H_2, formate, acetate, methanol, methyl sulfides and methylamines. These substrates are primarily produced by the decomposition of organic matter by other bacteria and fungi present in the surrounding microbial communities. Methanogenesis happens in the absence of oxygen and other electron acceptors like nitrate, sulphate and iron.").

2 Khanna K. (6 May 2022) *How Methanogenic Archaea Contribute to Climate Change*, American Society for Microbiology ("Among animals, ruminants are key contributors to climate change. This is because their burps contain a huge amount of methane. In fact, cattle are among the leading cause of agricultural greenhouse gas emissions. A single cow can produce ~150-500 g of methane/day, depending on the breed. Ruminants differ from other animals in that they have specialized digestive systems comprised of stomachs that have 4 compartments instead of 1. Rumen, the largest compartment in the stomach, is the hub for digestion of feed by microbes, including bacteria and fungi. The enteric fermentation of feed produces hydrogen and carbon dioxide, which are used by methanogens present in the rumen to produce methane. The greenhouse gas is then belched or burped out of the rumen, to the atmosphere, via the esophagus.").

3 *See generally* Reisinger A., Clark H., Cowie A. L., Emmet-Booth J., Gonzalez Fischer C., Herrero M., Howden M., & Leahy S. (2021) *How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals?*, Philos. Trans. R. Soc. A. 379(2210): 20200452.

4 Khanna K. (6 May 2022) *How Methanogenic Archaea Contribute to Climate Change*, American Society for Microbiology ("Among animals, ruminants are key contributors to climate change. This is because their burps contain a huge amount of methane. In fact, cattle are among the leading cause of agricultural greenhouse gas emissions. A single cow can produce ~150-500 g of methane/day, depending on the breed. Ruminants differ from other animals in that they have specialized digestive systems comprised of stomachs that have 4 compartments instead of 1. Rumen, the largest compartment in the stomach, is the hub for digestion of feed by microbes, including bacteria and fungi. The enteric fermentation of feed produces hydrogen and carbon dioxide, which are used by methanogens present in the rumen to produce methane. The greenhouse gas is then belched or burped out of the rumen, to the atmosphere, via the esophagus.").

5 Pandey H. O., & Upadhyay D. (2022) *Chapter 3: Global livestock production systems: Classification, status, and future trends* in Emerging Issues in Climate Smart Livestock Production, Mondal S. & Singh R. L. (eds.), 47–70, 52 (*see* Figure 1 *showing* livestock production system classification).

6 Pandey H. O., & Upadhyay D. (2022) *Chapter 3: Global livestock production systems: Classification, status, and future trends* in Emerging Issues in Climate Smart Livestock Production, Mondal S. & Singh R. L. (eds.), 47–70, 50 ("Livestock production systems (LPS) are essentially subsets within the agriculture sector. LPS can be classified in different ways based on various criteria. They may be the integration of livestock with crop production, the availability of land, the intensity of production, the type of product, the agro-ecological zone, commercialization, etc.").

7 Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, White Paper, 8 ("That has an important effect because the first use of feed by an animal is to support its own maintenance: the energy an animal needs to live. It is the surplus of energy in feed over maintenance requirements that can contribute to milk production, or to weight gain,

which means the addition of meat. Although cattle need a balance of different types of feed, in general, cattle fed more digestible feeds can eat more, produce more milk and grow faster than cattle fed less digestible feeds. Although they produce more methane per animal, the methane per kilogram of milk or meat decreases.").

8 Parish J. A., Rivera J. D., & Boland, H. T. (2022) *Understanding the Ruminant Animal Digestive System*, Mississippi State University Extension, Publication 2503, 1 ("Ruminant livestock include cattle, sheep, and goats. Ruminants are hoofed mammals that have a unique digestive system that allows them to better use energy from fibrous plant material than other herbivores. Unlike monogastrics such as swine and poultry, ruminants have a digestive system designed to ferment feedstuffs and provide precursors for energy for the animal to use.").

9 Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture,* Princeton University School of Public and International Affairs, White Paper, 6 ("Ruminants contain a portion of the stomach, known as the rumen, which supports the microbial populations able to break down cellulose. This ability allows these animals to survive on diets of grasses, leaves, high-fiber byproducts and other "fodders." Microorganisms known as archaea, which are ultimately the source of all methane on earth, use the hydrogen that is released by other microorganisms in the rumen to produce methane.").

10 Li J., Sun S., Sharma D., Ho M. S., & Liu H. (2023) *Tracking the drivers of global greenhouse gas emissions with spillover effects in the post-financial crisis era*, Energy Policy 174(113464): 1–10, 2 ("A spillover effect is defined as the impacts on emissions outside the region that is making GHG mitigation efforts (Engström et al., 2021). The spillover effects across economies via global supply chains may have significant impacts on global GHG emissions thus deserves special attention for two main reasons. First, most GHG mitigating actions in countries are made at the national level, not in coordination with other countries, except the European Union. Such national policies do not consider these spillover effects, at least not directly (there may be considerations of leakage and border adjustments). Second, as Engström et al. (2021) noted, the strongest mitigation efforts in most countries are planned for the future, such as carbon neutrality commitments for 2050.").

11 Herrero M., Henderson B., Havlik P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. H., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, Nat. Clim. Change 6(5): 452–461, 458 ("Emissions leakage. This occurs when the mitigation policies used to reduce livestock emissions in one region cause production to fall, increasing the imports of livestock commodities to that region, thereby raising production and associated emissions in the exporting regions. This market-based migration of production can potentially lower the efficacy of mitigation policies, but if policies rely on positive incentives such as mitigation subsidies rather than negative incentives such as a carbon tax, it may be possible to reduce emissions without lowering production and thereby prevent leakage. If negative incentives are used, leakage can only be eliminated if the incentives are applied to all global livestock emissions. Annual reductions in livestock emissions of 163 $MtCO_2e\ yr^{-1}$ have been estimated in response to a US$27 per tCO_2e carbon tax on agricultural emissions in industrialized (Annex I) countries[82]. However, 35% of this reduction in emissions is estimated to be offset by increased emissions in developing (non-Annex I) countries. A sensitivity analysis of the trade elasticities, which are critical determinants of the leakage rate, placed the mean leakage rate (with a 95% confidence) between 16% and 56%.").

12 Herrero M., & Thornton P. K. (2011) *Production systems for the future: balancing trade-offs between food production, efficiency, livelihoods and the environment* *in* Proceedings of the 5th World Congress on Conservation Agriculture: *Incorporating 3rd Farming Systems Design Conference*, 12 ("Sustainable agricultural intensification has received significant attention as a mechanism for increasing food production for feeding 9 billion people (Foresight 2011). Some of the benefits mentioned include higher resource use efficiency (water, nutrients, land), less greenhouse gas emissions per unit of product, land

sparing impacts and reductions in deforestation, and others (Royal Society 2009). Defining the limits to agricultural intensification is crucial for developing regulatory frameworks for sustainable food production and for maintaining ecosystems functions.”).

13 Rattalino Edreira J. I., Andrade J. F., Cassman K. G., Van Ittersum M. K., Van Loon M. P., & Grassini P. (2021), *Spatial frameworks for the robust estimation of yield gaps*, Nat. Food 2(10): 773–779, 773 (“The yield gap, defined as the difference between actual farm yield and the yield potential with good management that minimizes yield losses from biotic and abiotic stresses, is a key biophysical indicator of the available room for crop production increase with current land and water resources[6].”).

14 Methane emissions due to human activity have already caused 0.51 °C of the 1.06 °C of total observed warming (2010–2019) compared to pre-industrial, according to Figure SPM.2 in Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, in Climate Change 2021: *The Physical Science Basis*, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* Masson-Delmotte V., et al. (eds.). See also United Nations Environment Programme and Climate & Clean Air Coalition (2022) *Summary for Policymakers*, in Global Methane Assessment: *2030 Baseline Report*, 5 (“The Intergovernmental Panel on Climate Change (IPCC)’s Sixth Assessment shows that human-driven methane emissions are responsible for nearly 45 per cent of current net warming. The IPCC has continuously emphasized the critical urgency of reducing anthropogenic emissions – from methane and from other climate pollutants – if the world is to stay below 1.5° and 2°C targets.”).

15 Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, in Climate Change 2021: *The Physical Science Basis*, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* Masson-Delmotte V., *et al.* (eds.), SPM-36 (“Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality.”). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in Climate Change 2021: *The Physical Science Basis*, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 (“Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). {6.6.3, 6.7.3, 4.4.4}”); *and* Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, in Climate Change 2022: *Impacts, Adaptation, and Vulnerability*, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), SPM-11, SPM-13 (“Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (*high confidence*).”; “Levels of risk for all Reasons for Concern (RFC) are assessed to become high to very high at lower global warming levels than in AR5 (high confidence). Between 1.2°C and 4.5°C global warming level very high risks emerge in all five RFCs compared to just two RFCs in AR5 (*high confidence*). Two of these transitions from high to very high risk are associated with near-term warming: risks to unique and threatened systems at a median value of 1.5°C [1.2 to 2.0] °C (*high confidence*) and risks associated with extreme weather events at a median value of 2°C [1.8 to 2.5] °C (*medium confidence*). Some key risks contributing to the RFCs are projected to lead to widespread, pervasive, and potentially irreversible impacts at global warming levels of 1.5–2°C if exposure and vulnerability are high and adaptation is low (*medium confidence*).”; “B.3 Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans (*very high confidence*). The level of risk will depend on concurrent near-term trends in vulnerability, exposure, level of socioeconomic development and adaptation (*high confidence*).”).

16 Permafrost Pathways, *Mitigation policy* (*last visited* 9 June 2023) ("Depending on how hot we let it get, carbon emissions from Arctic permafrost thaw are expected to be in the range of 30 to more than 150 billion tons of carbon (110 to more than 550 Gt CO$_2$) this century, with upper estimates on par with the cumulative emissions from the entire United States at its current rate. To put it another way, permafrost thaw emissions could use up between 25 and 40 percent of the remaining carbon budget that would be necessary to cap warming at the internationally agreed-upon 2 degrees Celsius global temperature threshold established in the Paris Agreement."); *data from* Schuur E. A. G., McGuire A. D., Schädel C., Grosse G., Harden J. W., Hayes D. J., Hugelius G., Koven C. D., Kuhry P., Lawrence D. M., Natali S. M., Olefeldt D., Romanovsky V. E., Schaefer K., Turetsky M. R., Treat C. C., & Vonk J. E. (2015) *Climate change and the permafrost carbon feedback*, Nature 520(7546): 171–179.

17 Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, Science 377(6611): 1–10, 7 ("Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS and GrIS tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF, and abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST returns below 1.5°C within an uncertain overshoot time (likely decades) (94)."). *See also* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: *Climate Change 2023*, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).").

18 The *Global Methane Pledge* calls for reducing global methane emissions by at least 30 percent from 2020 levels by 2030, which is comparable to 35 percent reduction below 2030 business-as-usual projections and within the range found to be consistent with 1.5 °C pathways in Figure ES1 of the *Global Methane Assessment*. *See* United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: *Benefits and Costs of Mitigating Methane Emissions*; and United Nations Environment Programme & Climate & Clean Air Coalition (2021) Briefing on the Global Methane Pledge ("The Global Methane Pledge is a strong first step as the first-ever Heads-of State global commitment to cut methane emissions at a level consistent with a 1.5 C pathway."). *See also* United States Department of State (11 October 2021) Joint U.S.-EU Statement on the Global Methane Pledge, Press Release ("Countries joining the Global Methane Pledge commit to a collective goal of reducing global methane emissions by at least 30 percent from 2020 levels by 2030 and moving towards using highest tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. Successful implementation of the Pledge would reduce warming by at least 0.2 degrees Celsius by 2050.").

19 Methane emissions in 2017 from ruminants due to enteric fermentation and manure is estimated at 115 (110–121) million metric tons of methane (Mt CH$_4$) compared with approximately 380 Mt CH$_4$ total anthropogenic methane emissions (Table 3 in Saunois *et al.*, 2020). This is slightly lower than estimated by the Food and Agricultural Organization (FAO) of the United Nations for 2005 of 124 Mt CH$_4$ (converting 3.1 GtCO$_2$e using IPCC AR4 GWP$_{100}$ value of 25). Saunois M., *et al.* (2020) *The Global Methane Budget 2000–2017*, Earth System Science Data 12(3): 1561–1623. *See also* Gerber P. J., Steinfeld H., Henderson B., Mottet A., Opio C., Dijkman J., Falcucci A., & Tempio G. (2013) Tackling

climate change through livestock: *a global assessment of emissions and mitigation opportunities*, Food and Agriculture Organization of the United Nations: Rome, 15 ("Total GHG emissions from livestock supply chains are estimated at 7.1 gigatonnes CO_2-eq per annum for the 2005 reference period. They represent 14.5 percent of all human-induced emissions using the most recent IPCC estimates for total anthropogenic emissions (49 gigatonnes CO_2-eq for the year 2004; IPCC, 2007)… 3.1 gigatonnes CO_2-eq of CH_4 per annum, or 44 percent of anthropogenic CH_4 emissions (IPCC, 2007).").

20 Gerber P. J., Steinfeld H., Henderson B., Mottet A., Opio C., Dijkman J., Falcucci A., & Tempio G. (2013) Tackling climate change through livestock: *a global assessment of emissions and mitigation opportunities*, Food and Agriculture Organization of the United Nations: Rome, 17 (Figure 4 shows contributions to the 7.1 $GtCO_2e$ total livestock emissions with 39.1% from enteric methane and 4.3% from manure management methane.).

21 Swanson Z., Welsh C., & Majkut J. (May 2023) Mitigating Risk and Capturing Opportunity: *The Future of Alternative Proteins*, Center for Strategic & International Studies, 1–2 ("Today, countries and companies are seeking to change the way they produce food to reduce the impact that food production contributes to climate and disease risks, as well as to improve domestic food security through reduced vulnerability to global shocks. One solution to address these challenges may come from "new" types of food that provide the experience of meat but require fewer inputs, have shorter and more adaptable supply chains, produce fewer greenhouse gas (GHG) emissions, and can be made in settings and regions not capable of sustaining animal agriculture. These are known as alternative proteins."); *and* Climate Advisers (2022) Reducing Methane from Food and Agriculture: *Opportunities for U.S. Leadership*, 18 ("Work with allies to develop an incubator for key technologies. The Biden administration should work to rally countries committed to climate action (especially Methane Pledge participants) to fund a facility that would undertake the initial steps to develop key mitigation technologies before handing them off to private actors to take to them to scale. Promising possibilities include drugs and feed additives to reduce emissions from enteric fermentation, higher-yielding varieties of rice, and alternative proteins.").

22 Non-Annex I countries are "mostly developing countries [that] are recognized by the [United Nations Framework] Convention [on Climate Change] as being especially vulnerable to the adverse impacts of climate change, including countries with low-lying coastal areas and those prone to desertification and drought", *see* United Nations Framework Convention on Climate Change, Parties & Observers (*last visited* 21 November 2023). This brief aims to identify solutions applicable to low to middle-income countries as defined by the World Bank, a majority of which are non-annex I countries (63 of 82). For a list of low and middle income economies, *see* The World Bank, World Bank Country and Lending Groups (*last visited 21* November 2023).

23 Herrero M., Henderson B., Havlik P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. H., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) Greenhouse gas mitigation potentials in the livestock sector, Nat. Clim. Change 6(5): 452–461, 453 ("The developing world (non-Annex 1 countries; see Supplementary Information) contributes 70% of non-CO_2 emissions from ruminants and 53% from monogastrics[13], and this share is expected to grow as livestock production increases to meet demand growth in the developing world. Mixed crop–livestock systems dominate livestock emissions (58% of total emissions) largely because of their prevalence, whereas grazing-based systems contribute 19% (ref. 13). Industrial and other systems comprise the rest.").

24 Charmley E., *et al.* (2015) A universal equation to predict methane production of forage-fed cattle in Australia, Anim. Prod. Sci. 56(3): 169–180, 169 ("Records were obtained from dairy cattle fed temperate forages (220 records), beef cattle fed temperate forages (680 records) and beef cattle fed tropical forages (133 records). Relationships were very similar for all three production categories and single relationships for [methane production (MP)] on a [dry matter intake (DMI)] or [gross energy intake (GEI)] basis were proposed for national inventory purposes. These relationships were MP (g/day) = 20.7

(±0.28) × DMI (kg/day) ($R^2 = 0.92$, $P < 0.001$) and MP (MJ/day) = 0.063 (±0.008) × GEI (MJ/day) ($R^2 = 0.93$, $P < 0.001$).”).

25 Balehegn M., Duncan A., Tolera A., Ayantunde A. A., Issa S., Karimou M., Zampaligré N., André K., Gnanda I., Varijakshapanicker P., Kebreab E., Dubeux J., Boote K., Minta M., Feyissa F., & Adesogan A. T. (2020) Improving adoption of technologies and interventions for increasing supply of quality livestock feed in low- and middle-income countries, Glob. Food Secur. 26: 1–11, 6 (“Despite the challenges described above, several introduced feed technologies have improved supply of quality feed and livestock productivity and have been successfully adopted, scaled and some have directly increased incomes (White et al., 2013). Examples include brown midrib sorghum in central America (Rodriguez, 2013), *Desho* grass in Ethiopia (Asmare et al., 2016), *Brachiaria* in Brazil and Kenya (Jank et al., 2014; Maina et al., 2019), cowpea in West Africa (Tarawali et al., 2002), corn silage production in semi-arid China (Gansu Economic Daily, 2018) and *Ficus thonninningii* trees in northern Ethiopia (Balehegn et al., 2014a). Table 3 describes some successful feed improvement technologies in various LMIC and agro-ecologies.”).

26 Van Zanten H. H. E., Simon W., Van Selm B., Wacker J., Frehner A., Hijbeek R., Van Ittersum M. K., & Herrero M. (2023) Circularity in Europe strengthens the sustainability of the global food system, Nat. Food 4: 320–330, 322. (“Applying circularity principles, that is, feeding animals with by-products, food waste and grass, necessitates a radical redesign of the livestock sector (Fig. 5).”).

27 Herrero M., Palmer J., & Mason-D’Croz D. (2019) *Finding the sweetspots: Trade-offs between productivity increases, structural change and the mitigation potential of dairy systems in Ethiopia*. Report for the Gates Foundation. Commonwealth Scientific and Industrial Research Organisation, Brisbane, Australia, 24 pp.

28 *See e.g.* Duncan A. J., Teufel N., Mekonnen K., Singh V. K., Bitew A., & Gebremedhin B. (2013) Dairy intensification in developing countries: effects of market quality on farm-level feeding and breeding practices, Animal 7(12): 2054–62, 2054 (“However, as for Ethiopia, there is considerable scope for closing yield gaps in India through improved feed use and supply. Results strongly show that well-developed markets with good procurement arrangements are key for sustainable dairy intensification.”); Minten B., Tamru S., & Reardon T. (2021) Post-harvest losses in rural-urban value chains: Evidence from Ethiopia, Food Policy 98 101860: 1–11, 1 (“We study post-harvest losses (PHL) in important and rapidly growing rural-urban value chains in Ethiopia. We analyze self-reported PHL from different value chain agents – farmers, wholesale traders, processors, and retailers – based on unique large-scale data sets for two major commercial commodities, the storable staple teff and the perishable liquid milk. PHL in the most prevalent value chain pathways for teff and milk amount to between 2.2 and 3.3 percent and 2.1 and 4.3 percent of total produced quantities, respectively. We complement these findings with primary data from urban food retailers for more than 4,000 commodities. Estimates of PHL from this research overall are found to be significantly lower than is commonly assumed. We further find that the emerging modern retail sector in Ethiopia is characterized by half the level of PHL than are observed in the traditional retail sector. This is likely due to more stringent quality requirements at procurement, sales of more packaged – and therefore better protected – commodities, and better refrigeration, storage, and sales facilities.”); and Bryan E., Ringler C., Okoba B., Koo J., Herrero M., & Silvestri S. (2013) Can agriculture support climate change adaptation, greenhouse gas mitigation and rural livelihoods? insights from Kenya, Climatic Change 118(2): 151–165, 162 (“Promoting the adoption of triple-win strategies will be a major challenge. The extensive literature on constraints to the adoption of agricultural technologies and practices shows that there are several factors that impede uptake, such as lack of information, risk aversion, lack of access to input and output markets, and lack of financial incentives (Barrett et al. 2002; Ehui and Pender 2005; Lee 2005; Herrero et al. 2010b; McDermott et al. 2010). Overcoming these obstacles will require targeted investments to make smallholder systems more market-oriented (Herrero et al. 2010b; McDermott et al. 2010). Indeed, farmers in Kenya with access to input and output markets have been shown to have higher use of inputs, such as fertilizer, and greater

productivity (Owuor 1999; Strasberg et al. 1999). Strengthening the quality and delivery of information services is also critical, particularly because triple-win strategies are location-specific (based on the local agroecology, climate factors, soil characteristics, livelihood systems, socio-economic conditions, etc.) as this article and many others have shown (Solano et al. 2000; Ehui and Pender 2005; Lee 2005; Kato et al. 2011; Silvestri et al. 2012).").

29 Precision Development's approach to building scalable farmer-centric services by leveraging Information and Communication Technology (ICT) offers examples of this recommendation in practice. Digital Green's AI focused approach to farmer extension is another example.

30 Food and Agriculture Organization of the United Nations, International Fund for Agriculture Development, United Nations Children's Fund, World Food Programme, & World Health Organization (2023) THE STATE OF FOOD SECURITY AND NUTRITION IN THE WORLD 2023: Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum, xvi ("Global hunger, measured by the prevalence of undernourishment (Sustainable Development Goal [SDG] Indicator 2.1.1), remained relatively unchanged from 2021 to 2022 but is still far above pre-COVID-19-pandemic levels, affecting around 9.2 percent of the world population in 2022 compared with 7.9 percent in 2019."; "Conflict, climate change and the enduring secondary effects of the COVID-19 pandemic continue to affect malnutrition, birthweights and caring practices like exclusive breastfeeding.").

31 Food and Agriculture Organization of the United Nations, International Fund for Agriculture Development, United Nations Children's Fund, World Food Programme, & World Health Organization (2023) THE STATE OF FOOD SECURITY AND NUTRITION IN THE WORLD 2023: Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum, 143 ("The report has repeatedly highlighted that the intensification and interaction of conflict, climate extremes and economic slowdowns and downturns, combined with highly unaffordable nutritious foods and growing inequality, are pushing us off track to meet the SDG 2 targets. While policy recommendations have been offered to build resilience against these adversities, this year the report underscores the importance of also considering other important megatrends.").

32 Arndt C., *et al.* (2022) Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050, PROC. NATL. ACAD. SCI. 119(20): e2111294119, 1–10, 2 ("In addition, human population growth is generally high in LMIC, while consumption of animal-sourced food is often below recommended dietary levels or reliant upon ruminant meat and milk for livelihoods and nutrition security (10, 11)"). *See also* Herrero M., & Thornton P. K. (2013) Livestock and global change: Emerging issues for sustainable food systems, PROC. NATL. ACAD. SCI. 110(52): 20878–81, 20878 ("The supply response of the global agriculture and livestock sectors, if current trends continue, is likely to be able to accommodate these demand increases (5). Most recent projections have important common features: - Local production under current yield trends in many parts of the world, like Sub-Saharan Africa (SSA) and parts of Asia, will not be able to meet local food demand. Hence, increases in food trade are projected to increase in the future in some parts of the world. This is a key aspect of balancing the food supply and demand equation. - Although increases in the yields of crops and livestock have occurred in most regions of the world (apart from SSA), projections show a variable increase in cropland and grassland expansion to meet demand (7).").

33 Arndt C., *et al.* (2022) Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050, PROC. NATL. ACAD. SCI. 119(20): e2111294119, 1–10, 2 ("In contrast, in high-income countries (HIC) population growth is much lower and the consumption of animal protein is often above recommended dietary levels (9, 11).").

34 United Nations, Population (*last visited* 25 July 2023) ("The world's population is more than three times larger than it was in the mid-twentieth century. The global human population reached 8.0 billion in mid-November 2022 from an estimated 2.5 billion people in 1950, adding 1 billion people since 2010 and 2 billion since 1998. The world's population is expected to increase by nearly 2 billion persons in the

next 30 years, from the current 8 billion to 9.7 billion in 2050 and could peak at nearly 10.4 billion in the mid-2080s.”).

35 Van Dijk M., Morley T., Rau M. L., & Saghai Y. (2021) A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050, Nat. Food 2(7): 494–501, 498 (“Projections that account for climate change show a somewhat wider range of outcomes (−1% to +20% for per capita food demand, +30% to +62% for total food demand and −91% to +30% for population at risk of hunger).”).

36 *See* Figure 6.1 Growth in meat production and consumption on a protein basis, 2021 to 2030 for percentages of production of meats as lower percentages than consumption of meats in all categories except Upper-middle income countries *in* Organisation for Economic Co-operation and Development, & Food and Agriculture Organization of the United Nations (2023) OECD-FAO Agricultural Outlook 2023-2032, 165.

37 Skea J., *et al.* (2022) *Summary for Policymakers* in Climate Change 2022: *Mitigation of Climate Change, Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-10 (“The annual average during the decade 2010–2019 was 56 ± 6.0 GtCO$_2$-eq, 9.1 GtCO$_2$-eq yr^{-1} higher than in 2000–2009.”). *See also* Zhu J., Luo Z., Sun T., Li W., Zhou W., Wang X., Fei X., Tong H., & Yin K. (2023) *Cradle-to-grave emissions from food loss and waste represent half of total greenhouse gas emissions from food systems*, Nat. Food 4: 1–13, 2 (“The global food system generated 18.6 ± 12.6 (1*σ*) Gt of CO$_2$ equivalent (GtCO$_2$e) GHGs in 2017 (Fig. 1) in four food categories (cereals, pulses and others; roots and oil crops; vegetables and fruit; and meat and animal products).”).

38 Global Methane Hub & Climateworks Foundation (April 2023) The Global Innovation Needs Assessments: *Food System Methane*, 6 (“Methane represents approximately a fifth of global greenhouse gases, 60% of which arise from the food system. An estimated 10.3 GtCO$_2$e of methane are emitted per year. Food system methane accounts for an estimated 6-7 GtCO$_2$e, including emissions arising from the agriculture sector (40% share of total methane) as well as waste emissions associated with food waste.”).

39 Note that this analysis assumes dietary patterns will remain consistent. However, several other studies find that dietary patterns are expected to experience many changes as the population grows and the demand for protein increases along with GDP per capita: Ivanovich C. C., Sun T., Gordon D. R., & Ocko I. B. (2023) *Future warming from global food consumption*, Nat. Clim. Change 13: 1–14, 1 (“We find that global food consumption alone could add nearly 1 °C to warming by 2100. Seventy five percent of this warming is driven by foods that are high sources of methane (ruminant meat, dairy and rice).”). *See also* Arndt C., *et al.* (2022) *Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050*, Proc. Natl. Acad. Sci. 119(20): e2111294119, 1–10, 7 (“The five ABS strategies reduced product-based CH$_4$ emissions by an average of 17% (ranging from 12 to 32%) and daily CH$_4$ emissions by an average of 21% (ranging from 12 to 35%). The 100% adoption of only one of the PB or ABS strategies at a time cannot sufficiently decrease global enteric CH$_4$ emissions from agriculture by 2030 or 2050 to achieve the 1.5°C target.”).

40 Herrero M. & Thornton P. K. (2013) *Livestock and global change: Emerging issues for sustainable food systems*, Proc. Natl. Acad. Sci. 110(52): 20878–20881, 20878 (“- Animal numbers will increase. But monogastric production (pork and poultry) will grow at faster rates than ruminants (meat especially, and less so for milk). - These factors lead to net increases in greenhouse gas emissions (GHG) from the agricultural and livestock sectors, but a diminishing trend in the emissions intensities across commodities (GHG per unit of product).”).

41 See ref. 40.

42 Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., & Tempio, G. (2013) Tackling climate change through livestock – *A global assessment of emissions and mitigation opportunities*, Food and Agriculture Organization of the United Nations, Rome, 23 ("GHG emissions from cattle represent about 65 percent of the livestock sector emissions (4.6 gigatonnes CO_2-eq), making cattle the largest contributor to total sector emissions. Beef production contributes 2.9 gigatonnes or 41 percent of total sector emissions while emissions from milk production amount to 1.4 gigatonnes or 20 percent of total sector emissions.[11] Emissions allocated to other goods and services such as animal draught power and manure used as fuel represent 0.3 gigatonnes (Figure 10)."). *See also* Figure 3b for breakdown of GHG emissions from animal-based food commodities in Xu X., Sharma P., Shu S., Lin T.-S., Ciais P., Tubiello F. N., Smith P., Campbell N., & Jain A. K. (2021) *Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods*, Nat. Food 2(9): 724–732.

43 Jackson R. B., Saunois M., Bousquet P., Canadell J. G., Poulter B., Stavert A. R., Bergamaschi P., Niwa Y., Segers A., & Tsuruta A. (2020) *Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources*, Environ. Res. Lett. 15(7): 071002 (*See* Table 1 for methane emissions from enteric fermentation processes). *See also* Arndt C., *et al*. (2022) *Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050*, Proc. Natl. Acad. Sci. 119(20): e2111294119, 1–10, 1 ("Among food-related GHG emissions, methane (CH_4) from livestock contributes 30% of the global anthropogenic CH_4 emissions (2), 17% of the global food system GHG emissions, and 5% of global GHG emissions (2, 3).").

44 Food and Agriculture Organization of the United Nations (7 May 2020) *Land use in agriculture by the numbers* ("Globally agricultural land area is approximately five billion hectares, or 38 percent of the global land surface. About one-third of this is used as cropland, while the remaining two-thirds consist of meadows and pastures) for grazing livestock.").

45 Davis K. F., Yu K., Herrero M., Havlik P., Carr J. A., & D'Odorico P. (2015) *Historical trade-offs of livestock's environmental impacts*, Environ. Res. Lett. 10(12): 125013, 1–10, 1 ("We find that [environmental burdens per animal calorie (EBCs)] have changed substantially for land (−62%), GHGs (−46%) and nitrogen (+188%). Changes in RUE (e.g., selective breeding, increased grain-feeding) have been the primary contributor to these EBC trends, but shifts in the composition of livestock production were responsible for 12%–41% of the total EBC changes."); *and* Herrero M., Henderson B., Havlík P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. N., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, Nat. Clim. Change 6(5): 452–61, 455 ("Increased livestock and crop/pasture productivity. Practices that increase livestock, crop and pasture productivity have received significant attention in the past years, due to their multiple mitigation benefits. They can improve the GHG emission intensities of different livestock products, but they can also have indirect benefits associated with land use sparing, and could promote structural changes in the livestock sector. This section briefly describes these mitigation benefits.").

46 Xu X., Sharma P., Shu S., Lin T.-S., Ciais P., Tubiello F. N., Smith P., Campbell N., & Jain A. K. (2021) *Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods*, Nat. Food 2(9): 724–732, 724 ("Global GHG emissions from the production of food were found to be 17,318 ± 1,675 $TgCO_2eq\ yr^{-1}$, of which 57% corresponds to the production of animal-based food (including livestock feed), 29% to plant-based foods and 14% to other utilizations. Farmland management and land-use change represented major shares of total emissions (38% and 29%, respectively), whereas rice and beef were the largest contributing plant- and animal-based commodities (12% and 25%, respectively), and South and Southeast Asia and South America were the largest emitters of production-based GHGs.").

47 Salou T., Le Mouël C., & Van Der Werf H. M. G. (2017) *Environmental impacts of dairy system intensification: the functional unit matters!*, J. Clean. Prod. 140, 445–54, 445 ("Furthermore, the choice of functional unit leads to radically different conclusions. Using only a mass-based functional unit, which is predominant in current life cycle assessment practice, does not provide a balanced view of the impacts of intensification and could mislead decision makers in identifying promising dairy systems. More generally, current LCA practice seems largely blind to the negative environmental consequences of agricultural system intensification, as revealed by the area-based functional unit.").

48 Garnett T. (2011) *Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)?*, Food Policy 36, S23–S32, S27 (*see* Table 1 for differences between how use of a certain metric can change what is considered "efficient").

49 Gutiérrez-Peña R., Mena Y., Batalla I., & Mancilla-Leytón J. M. (2019) *Carbon footprint of dairy goat production systems: A comparison of three contrasting grazing levels in the Sierra de Grazalema Natural Park (Southern Spain)*, J. Environ. Manage. 232, 993–998, 996 ("As observed in this study, using one hectare of UAL (Utilizable Agricultural Land) as a functional unit, [more intensified grazing (MIG)] farms had a significantly higher [carbon footprint (CF)] per hectare compared with [low productivity grazing (LPG)] and [high productivity grazing (HPG)] because of a large increase in off-farm emissions (Table 3)… Salvador et al. (2017), in small-scale mountain dairy farms in the Italian Alps, found that Lower Livestock Unit farms registered higher values of GHG emissions per kg of [fat and protein corrected milk (FPCM)] than Higher Livestock Unit farms (1.94 vs. 1.59 kg CO$_2$e kg^{-1} FPCM), nevertheless the situation was reversed upon considering the m^2 of Utilizable Agricultural Land as a functional unit (0.22 vs. 0.73 kg CO$_2$e m^{-2}). Likewise, Salou et al. (2017) who compared milk production systems in France, found a lower GWP per hectare in the grass-based, organic and highland systems compared with more intensified systems. This was due to the switch from grass-based feed to maize silage and concentrate feed."). *See also* Salvador S., Corazzin M., Romanzin A., & Bovolenta S. (2017) *Greenhouse gas balance of mountain dairy farms as affected by grassland carbon sequestration*, J. Environ. Manage. 196: 644–650; *and* Salou T., Le Mouël C., & Van Der Werf H. M. G. (2017) *Environmental impacts of dairy system intensification: the functional unit matters!*, J. Clean. Prod. 140: 445–454.

50 Salvador S., Corazzin M., Romanzin A., & Bovolenta S. (2017) *Greenhouse gas balance of mountain dairy farms as affected by grassland carbon sequestration*, J. Environ. Manage. 196: 644–650, 644 ("Performing no allocation, and using FPCM as the functional unit, slightly significant differences were found between the two groups of farms, and the values registered for LLU farms tended to be higher than for the HLU group (1.94 vs. 1.59 kg CO$_2$-eq/kg FPCM, P 0.10, Table 3). This result is consistent with other works that highlight how more extensive farms, less productive and less efficient from an environmental perspective, have a greater impact than intensive systems (Capper et al., 2009; Gerber et al., 2010)."). *See also* Batalla I., Knudsen M. T., Mogensen L., Hierro Ó. D., Pinto M., & Hermansen J. E. (2015) *Carbon footprint of milk from sheep farming systems in Northern Spain including soil carbon sequestration in grasslands*, J Clean. Prod. 104: 121–129, 128 ("This study shows the importance of including soil carbon sequestration in LCA, especially in farming systems where grass-lands are a substantial resource for animal feeding with high potentials of carbon sequestration. Nevertheless, there is a need to continue the development of strategies for a correct use and improvement of grasslands. Higher inputs from crop residues and manure increase the soil carbon sequestration. This study also indicates that grasslands used by extensive sheep farms plays an important role as carbon sinks.").

51 Gutiérrez-Peña R., Mena Y., Batalla I., & Mancilla-Leytón J. M. (2019) *Carbon footprint of dairy goat production systems: A comparison of three contrasting grazing levels in the Sierra de Grazalema Natural Park (Southern Spain)*, J. Environ. Manage. 232: 993–998, 997 ("When CF values are compared in the productive models considering GHG emissions and soil C sequestration, there are no longer any differences between the three groups. This is because total net emissions are reduced by 23–26% in the grazing system when soil C sequestration is considered in CF calculations (Table 2). These results

are similar to those found by Batalla et al. (2015) in sheep farming systems in northern Spain using the same methodology to estimate soil C sequestration (Petersen et al., 2013). Batalla et al. (2015) pointed out that the CF was reduced by 15% for semi-intensive systems with foreign breeds to 43% for semi-extensive systems with local breeds, when soil C sequestration was included.”).

52 Doran-Browne N. A., Eckard R. J., Behrendt R., & Kingwell R. S. (2015) *Nutrient density as a metric for comparing greenhouse gas emissions from food production*, Climatic Change 129(1–2): 73–87, 74 (“The metric t CO_2e/unit nutrient density was the preferred metric to use when examining GHGE from food production because it compares different types of products based on their nutritional value, rather than according to singular nutrients such as protein, or specific attributes such as product weight or energy content. Emissions/unit nutrient density has the potential to inform consumer choices regarding foods that have a higher nutritional content relative to the GHGE generated.”).

53 Saunois M., *et al.* (2020) *The Global Methane Budget 2000–2017*, Earth Syst. Sci. Data 12(3): 1561–1623, 1574–1575 (“Anaerobic conditions often characterize manure decomposition in a variety of manure management systems globally (e.g., liquid/slurry treated in lagoons, ponds, tanks, or pits), with the volatile solids in manure producing CH_4. In contrast, when manure is handled as a solid (e.g., in stacks or dry lots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and to produce little or no CH_4. However aerobic decomposition of manure tends to produce nitrous oxide (N_2O), which has a larger warming impact than CH_4. Ambient temperature, moisture, energy contents of the feed, manure composition, and manure storage or residency time affect the amount of CH_4 produced. Despite these complexities, most global datasets used herein apply a simplified IPCC Tier 1 approach, where amounts of manure treated depend on animal numbers and simplified climatic conditions by country.”).

54 Saunois M., *et al.* (2020) *The Global Methane Budget 2000–2017*, Earth Syst. Sci. Data 12(3): 1561–1623 (*see* Table 3 giving min-max range for total anthropogenic emissions of 359–407 $MtCH_4$ and ruminant methane emissions of 110–121 $MtCH_4$). This is slightly lower than estimated by the FAO for 2005 of 124 Mt CH_4 (converting 3.1 $GtCO_2$e using IPCC AR4 GWP_{100} value of 25). *See also* Gerber P. J., Steinfeld H., Henderson B., Mottet A., Opio C., Dijkman J., Falcucci A., & Tempio G. (2013) Tackling climate change through livestock: *A global assessment of emissions and mitigation opportunities*, Food and Agriculture Organization of the United Nations: Rome, 15 (“Total GHG emissions from livestock supply chains are estimated at 7.1 gigatonnes CO_2-eq per annum for the 2005 reference period. They represent 14.5 percent of all human-induced emissions using the most recent IPCC estimates for total anthropogenic emissions (49 gigatonnes CO_2-eq for the year 2004; IPCC, 2007)… 3.1 gigatonnes CO_2-eq of CH_4 per annum, or 44 percent of anthropogenic CH_4 emissions (IPCC, 2007).”).

55 Herrero M., Henderson B., Havlik P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. H., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, Nat. Clim. Change 6(5): 452–461, 453 (“The developing world (non-Annex 1 countries; see Supplementary Information) contributes 70% of non-CO_2 emissions from ruminants and 53% from monogastrics[13], and this share is expected to grow as livestock production increases to meet demand growth in the developing world. Mixed crop–livestock systems dominate livestock emissions (58% of total emissions) largely because of their prevalence, whereas grazing-based systems contribute 19% (ref. 13). Industrial and other systems comprise the rest.”).

56 Herrero M., Havlík P., Valin H., Notenbaert A., Rufino M. C., Thornton P. K., Blümmel M., Weiss F., Grace D., & Obersteiner M. (2013) *Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems*, Proc. Natl. Acad. Sci. 110(52): 20888–20893, 20890 (“The developing world contributes 75% of global GHG emissions from ruminants (Fig. 5A) and 56% of emissions from monogastrics. Mixed crop–livestock systems produce the bulk of emissions from ruminants (61%), and grazing systems account for 12% of emissions. Urban and other systems comprise the rest. Non-CO_2 emissions from different regions are largely driven by numbers of animals

and the predominant production systems, with SAS, LAM, SSA, and EUR having the highest total emissions (Fig. 5A)").

57 Chang J., Peng S., Yin Y., Ciais P., Havlik P., & Herrero M. (2021) *The Key Role of Production Efficiency Changes in Livestock Methane Emission Mitigation*, AGU ADVANCES 2(2): e2021AV000391, 1–16, 13 ("The higher emission intensities per kg of protein from either the 2019 MT or the 2019 T1 method, compared to the 2006 T1 method, led to projections of larger livestock methane emissions in the future, for a given scenario of livestock numbers and production from the FAO (2018). The projections using the new 2019 MT and 2019 T1 methods are 18%–21% and 24%–28% higher, respectively, than that given by the 2006 T1 method (Figures 4a–4c). Moving to the methodology of the *2019 IPCC Refinement(IPCC, 2019)* is important, as the differences can be substantial, particularly in regions such as Sub-Saharan Africa, Near East and North Africa, and South Asia, where large positive trends on livestock production (Figure S12) and emissions (Figure S13) are projected in the future scenarios. In the SSP database (Riahi et al., 2017) (https://tntcat.iiasa.ac.at/SspDb/), the projections for greenhouse gas emissions by Integrated Assessment Models (IAMs) were first harmonized for a base year of 2015 to the historical inventory from FAOSTAT. Our results suggest that using historical emissions from the FAOSTAT as a reference in the IAMs underestimates future emissions. The updated historical emissions by the 2019 MT and 2019 T1 methods in this study could be used as references in the IAMs. We further provided alternative pathways on emission intensity per kg of protein production based on country-specific past trend with the development of GDP per capita.").

58 Herrero M., Thornton P. K., Kruska R., & Reid R. S. (2008) *Systems dynamics and the spatial distribution of methane emissions from African domestic ruminants to 2030*, AGRIC. ECOSYST. ENVIRON. 126(1): 122–137, 123 ("However, currently, IPCC uses an average figure of 32 kg methane per tropical livestock unit (equivalent to an animal of 250 kg body weight) per year for African ruminants irrespective of production system and diet type (IPCC, 1997). This was due mainly to the difficulties encountered in obtaining data for applying Tier 2 methods in African countries (IPCC, 1997).").

59 Shroff J. (28 Sept 2022) *Why smallholder farmers are central to new food security interventions*, World Economic Forum ("The 600 million smallholder farmers around the world working on less than two hectares of land, are estimated to produce 28–31% of total crop production and 30–34% of food supply on 24% of gross agricultural area.").

60 Statista (2023) *Major producers of cow milk worldwide in 2023, by country* (see India as the third largest producer of cow milk at 99.5 million metric tons in 2023).

61 Food and Agriculture Organization of the United Nations, *India at a glance* (*last visited* 7 July 2023) ("Agriculture, with its allied sectors, is the largest source of livelihoods in India. 70 percent of its rural households still depend primarily on agriculture for their livelihood, with 82 percent of farmers being small and marginal.").

62 Statista (2023) Number of milk cows worldwide in 2023, by country (*see* India as the largest number of milk cows worldwide in 2023 at over 61 million cows).

63 Mayberry D., Ash A., Prestwidge D., Godde C. M., Henderson B., Duncan A., Blummel M., Ramana Reddy Y., & Herrero M. (2017) *Yield gap analyses to estimate attainable bovine milk yields and evaluate options to increase production in Ethiopia and India*, AGRIC. SYST. 155: 43–51, 44, 50 ("India is the largest milk producer in the world, producing 130 billion kg milk/year (Ministry of Agriculture, 2014b; Rao et al., 2014). Milk and other dairy products account for around two thirds of the value of the Indian livestock sector and support the livelihoods of nearly half of India's 147 million rural households. Dairy production is concentrated in the irrigated cropping zone, but large amounts of milk are also produced in rainfed areas. The majority of the cattle population consists of indigenous breeds, which have low milk yields of around 2 kg/head/day (Ministry of Agriculture, 2014a, 2014b). Most milk comes from buffalo, which comprise one third of the bovine population and produce around 5 kg milk/head/

day (Kumar and Parappurathu, 2014). Cattle diets are based almost entirely on crop residues and by-products, with contributions from grazing of natural pastures (Rao et al., 2014; Singh et al., 2008). Sub-optimal milk production is driven by low daily milk yields, short lactations (6–8 months) and long calving intervals (18–24 months) (Duncan et al., 2013).”; “Our analysis showed that there are considerable yield gaps for dairy production in areas of Ethiopia and India.”).

64 Herrero M., Thornton P. K., Gerber P., & Reid R. S. (2009) *Livestock, livelihoods and the environment: understanding the trade-offs*, Curr. Opin. Environ. Sustain. 1(2): 111–120, 114 (“The livestock and deforestation debate centers on two main phenomena related to different livestock production systems and their evolution. The first one is the direct conversion of forests into pastures for extensive cattle production, primarily in the neotropics [18]. According to several authors [18, 19, 20, 21] extensive cattle enterprises have been responsible for 65–80% of the deforestation of the Amazon (rate of forest loss of 18–24 million ha/yr). Some of these systems are changing and intensifying towards mixed crop/livestock systems and dairy production [20, 22, 23] as a result of new roads and markets and conversion of pastureland into cropland [18, 21, 22]. This is expected to reduce deforestation rates as farmers could increase efficiency and be able to obtain more product per unit of resource used [6], though this view has been recently contested [20]. At the same time, forest is directly cleared for growing crops, like soybeans, mostly to feed pigs and poultry in industrial systems and to provide a high protein source for concentrates of dairy cattle (0.4–0.6 million ha/yr) [18, 19, 21]. The rate of forest loss for crops is projected to increase as the demand for pig and poultry meat increases at faster rates than the consumption of red meats [6, 21].”). *See also* Herrero M., Henderson B., Havlík P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. N., Gerber P., Gill M., ButterbachBahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, Nat. Clim. Change 6(5): 452–461, 452 (“Intensification of production, in terms of increased livestock and/or crop productivity, has played a pivotal role in raising the output per unit of land and animal[1]. For example, in the USA, 60% more milk is produced now than in the 1940s with about 80% fewer cows[6]. Although intensification has occurred in some regions, agricultural land expansion has also been an important component of production growth in places such as Africa and Latin America. These trends, if continued, could drive significant increases in greenhouse gas (GHG) emissions, deforestation, loss of biodiversity and other negative impacts on the environment[7].”); *and* Wasley A. (2 June 2023) *More than 800m Amazon trees felled in six years to meet beef demand*, The Guardian (“A data-driven investigation by the Bureau of Investigative Journalism (TBIJ), the Guardian, Repórter Brasil and Forbidden Stories shows systematic and vast forest loss linked to cattle farming.”).

65 Herrero M., Henderson B., Havlík P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. N., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, Nat. Clim. Change 6(5): 452–461, 455 (“A recent review by Smith[59] indicates that this involves addressing the many unsustainable practices already manifest in the global food system. Many options for sustainable intensification exist, ranging from adoption of new technology to improving the efficiency of current food production. At the high-tech end are options such as the genetic modification of living organisms and the use of cloned livestock and nanotechnology[60–62]. By 2050 it may be possible to manipulate the traits controlled by many genes and confer desirable traits (such as improved nitrogen and water-use efficiency in crops) with improved productive characteristics[61]. But the future role of genetic manipulation in sustainable intensification is heavily dependent on the softening of public opposition, which is widespread in places.”).

66 Benton T. & Harwatt H. (2022) *Sustainable agriculture and food systems: Comparing contrasting and contested versions*, Research Paper, London: Royal Institute of International Affairs, 1–40, 12 (*see* Table 2 for key assumptions and critiques for sustainable intensification).

67 Mayberry D., Ash A., Prestwidge D., Godde C. M., Henderson B., Duncan A., Blummel M., Ramana Reddy Y., & Herrero M. (2017) *Yield gap analyses to estimate attainable bovine milk yields and evaluate*

options to increase production in Ethiopia and India, AGRIC. SYST. 155: 43–51, 49 ("Conversely, some interventions tested in our modelling could reduce labour requirements. Ashley et al. (2016) found that growing plots of improved forages near the house decreased labour requirements for raising cattle because less time was spent cutting grass from roadsides and/or herding cattle for grazing. Reduced labour requirements particularly benefited the children and women of the household, who were then able to spend more time at school or on other income-generating activities").

68 Herrero M., Thornton P. K., Gerber P., & Reid R. S. (2009) *Livestock, livelihoods and the environment: understanding the trade-offs*, CURR. OPIN. ENVIRON. SUSTAIN. 1(2): 111–120, 111 ("Livestock systems occupy 45% of the global surface area [4] and are a significant global asset with a value of at least $1.4 trillion. Livestock industries are also a significant source of livelihoods globally. They are organized in long market chains that employ at least 1.3 billion people globally and directly support the livelihoods of 600 million poor smallholder farmers in the developing world [1, 2]. Keeping livestock is an important risk reduction strategy for vulnerable communities, as animals can act as insurance when required. At the same time they are important providers of nutrients and traction for growing crops in smallholder systems [5]. Livestock are also an important source of nourishment. Livestock products contribute 17% to global kilocalorie consumption and 33% to protein consumption globally, but there are large differences between rich and poor countries [3]."). *See also* Thornton P. K. (2010) *Livestock production: recent trends, future prospects*, PHILOS. TRANS. R. SOC. B 365(1554): 2853–2867.

69 Swanson Z., Welsh C., & Majkut J. (May 2023) MITIGATING RISK AND CAPTURING OPPORTUNITY: *THE FUTURE OF ALTERNATIVE PROTEINS*, Center for Strategic & International Studies, 1–2 ("Today, countries and companies are seeking to change the way they produce food to reduce the impact that food production contributes to climate and disease risks, as well as to improve domestic food security through reduced vulnerability to global shocks. One solution to address these challenges may come from "new" types of food that provide the experience of meat but require fewer inputs, have shorter and more adaptable supply chains, produce fewer greenhouse gas (GHG) emissions, and can be made in settings and regions not capable of sustaining animal agriculture. These are known as alternative proteins."); *and* McBee J. D (2022) REDUCING METHANE FROM FOOD AND AGRICULTURE: *OPPORTUNITIES FOR U.S. LEADERSHIP*, Climate Advisers: 18 ("Work with allies to develop an incubator for key technologies. The Biden administration should work to rally countries committed to climate action (especially Methane Pledge participants) to fund a facility that would undertake the initial steps to develop key mitigation technologies before handing them off to private actors to take to them to scale. Promising possibilities include drugs and feed additives to reduce emissions from enteric fermentation, higher-yielding varieties of rice, and alternative proteins.").

70 Herrero M., Havlík P., Valin H., Notenbaert A., Rufino M. C., Thornton P. K., Blümmel M., Weiss F., Grace D., & Obersteiner M. (2013) *Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems*, PROC. NATL. ACAD. SCI. 110(52): 20888–20893, 20891 ("These high GHG emission intensities are driven by low animal productivity across large areas of arid lands, the use of low-quality feeds, feed scarcity, and animals with low productive potential that are often used for draft power and to manage household risk, as well as for production.").

71 Herrero M., Havlík P., Valin H., Notenbaert A., Rufino M. C., Thornton P. K., Blümmel M., Weiss F., Grace D., & Obersteiner M. (2013) *Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems,* PROC. NATL. ACAD. SCI. 110(52): 20888–20893, 20891 ("In most of the developed world emission intensities are low as a result of improved and more intensive feeding practices and temperate conditions, where feed quality is inherently higher.").

72 Herrero M., Havlík P., Valin H., Notenbaert A., Rufino M. C., Thornton P. K., Blümmel M., Weiss F., Grace D., & Obersteiner M. (2013) *Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems*, PROC. NATL. ACAD. SCI. 110(52): 20888–20893, 20890 ("The high production potential of livestock and a high level of intensification of production practices, such

as increased grain use in the developed world and in some of the highland mixed systems, results in high-quality diets (>10.5 MJME per kilogram DM). This finding explains the higher feed-use efficiencies in these regions.”).

73 Bryan E., Ringler C., Okoba B., Koo J., Herrero M., & Silvestri S. (2013) *Can agriculture support climate change adaptation, greenhouse gas mitigation and rural livelihoods? insights from Kenya*, Climatic Change 118(2): 151–65, 156 (“The relationship between the quality of the diet and manure and methane production follows well-established principles: higher quality diets and higher feed intake lead to greater methane production. However, methane production per unit of animal product decreases as the dietary quality improves. Therefore, supplementation with high-quality forages is both an important adaptation and GHG mitigation strategy.”).

74 Chang J., Peng S., Yin Y., Ciais P., Havlik P., & Herrero M. (2021) *The Key Role of Production Efficiency Changes in Livestock Methane Emission Mitigation*, AGU Advances 2(2): e2021AV000391, 1–16, 14 (“The continuation of past decreases in emission intensity, especially in developing countries, can be achieved through the transition of livestock production systems from extensive rangeland systems to mixed crop-livestock systems (Frank et al., 2018; Havlík et al., 2014), and through improving livestock management within the existing systems (Thornton & Herrero, 2010). Various factors can contribute to such a transition: for instance, better breeding, fertility and health intervention (Gill et al., 2010), better quality feed (Gill et al., 2010; Johnson & Johnson, 1995), and optimization of grazing management (e.g., forage storage to avoid losing weight in winter [Thornton & Herrero, 2010]). In addition, new technologies, such as feed supplements, can also reduce methane emissions from rumen (Caro et al., 2016; Gerber, Hristov, et al., 2013), while methane emissions from manure management can be mitigated through various options, such as improving housing systems, manure storage, composting, and anaerobic digestion (Gerber, Hristov, et al., 2013).”).

75 Bryan E., Ringler C., Okoba B., Koo J., Herrero M., & Silvestri S. (2013) *Can agriculture support climate change adaptation, greenhouse gas mitigation and rural livelihoods? insights from Kenya*, Climatic Change 118(2): 151–165, 154 (“Short-distance rangelands are the primary source of feed during the dry and wet seasons, while maize stover, roadside weeds, and cut-and-carry fodders represent other important sources of livestock feed. They also reported on changes in feed resource availability over the last 10 years as a result of drought, climate change, and land use change. Over this timeframe, some feed resources became unavailable, such as kikuyu grass; while new sources have become available, including napier grass (*Pennisetum purpureum*), desmodium (*Desmodium intortum*), mathenge (*Prosopis juliflora*), and calliandra (*Calliandra spp.*).”).

76 Bryan E., Ringler C., Okoba B., Koo J., Herrero M., & Silvestri S. (2013) *Can agriculture support climate change adaptation, greenhouse gas mitigation and rural livelihoods? insights from Kenya*, Climatic Change 118(2): 151–165, 162 (“Improved feeding practices, another key win-win-win strategy, are shown to increase the productivity of dairy cattle and net profits from the sale of milk in most cases, while reducing methane emissions per liter of milk produced.”).

77 Bampidis V., *et al.* (2021) *Safety and efficacy of a feed additive consisting of 3-nitrooxypropanol (Bovaer® 10) for ruminants for milk production and reproduction (DSM Nutritional Products Ltd)*, EFSA J. 19(11): 1–35, 1 (“Consequently, the FEEDAP Panel concluded that Bovaer® 10 was safe for dairy cows at the maximum recommended level. However, as a margin of safety could not be established, the FEEDAP Panel could not conclude on the safety of the additive for other animal species/categories. The FEEDAP Panel considered that the consumer was exposed to 3-nitrooxypropionic acid (NOPA), which is one of the 3-NOP metabolites. NOPA was not genotoxic based on the studies provided. The FEEDAP Panel concluded that the use of Bovaer® 10 in animal nutrition under the conditions of use proposed was of no concern for consumer safety and for the environment. The FEEDAP Panel concluded that the active substance 3-NOP may be harmful if inhaled. It is irritant (but not corrosive) to skin, irritant to the eyes but it is not a skin sensitiser. As the genotoxicity of 3-NOP is not completely

elucidated, the exposure through inhalation of the additive may represent an additional risk for the user.").

78 Byrne J. (5 July 2023) *dsm-firmenich: Bovaer has saved 50,000 tons of CO2e to date*, FEED NAVIGATOR ("Authorities recently approved the sale of Bovaer in Paraguay, for use in dairy and beef cattle, making it the seventh country in Latin America to give the feed additives the green light, while Elanco Animal Health, dsm-firmenich's strategic partner for developing, manufacturing, and commercializing Bovaer in the US, anticipates US approval and launch of the supplement in the first half of 2024."). *See also* de Sousa A. (9 September 2021) *World's Top Beef Supplier Approves Methane-Busting Cow Feed*, BLOOMBERG ("Latin America is the first region to grant approvals for the DSM product, which is also trying to get permission in the European Union, the U.S. and New Zealand. A trial on Brazilian beef showed Bovaer cut methane emissions from cows' stomachs by as much as 55%, the company said. Bovaer has undergone trials in 13 countries, with more than 48 peer-reviewed studies published."); *and* Bryce E. (30 September 2021) Kowbucha, seaweed, vaccines: the race to reduce cows' methane emissions, THE GUARDIAN ("There are dozens more livestock methane interventions under development, according to a recent assessment co-authored by Ermias Kebreab. But only a handful – including Bovaer and Zelp – have reached the market. Even here, there's still fine-tuning to be done. For instance Bovaer needs to be constantly in the rumen to work, meaning it may be less practical for free-ranging cattle whose feeding is less controlled (van Nieuwland said DSM is working to develop slow-release 3-NOP to help with this).").

79 Kliem K. E., Humphries D. J., Kirton P., Givens D. I., & Reynolds C. K. (2019) *Differential effects of oilseed supplements on methane production and milk fatty acid concentrations in dairy cows*, ANIMAL 13(2): 309–317, 309–10 ("It is well established that feeding supplemental fat (excluding calcium salts) to ruminants can reduce methane production, both on a daily and dry matter intake (DMI) basis (Beauchemin et al., 2009; Martin et al., 2010; Grainger and Beauchemin, 2011), the main reason being that supplemental lipids provide metabolizable energy (ME) to the diet which is not fermented, therefore reducing excess hydrogen available for methane synthesis. It is also suggested that lipid supplements rich in monounsaturated fatty acids (MUFA) or polyunsaturated fatty acids (PUFA) provide an alternative to methane synthesis for hydrogen disposal in the rumen (Clapperton, 1974; Fievez et al., 2003). In addition, some FA can have direct toxic effects on cellulolytic microbes and fibre digestion, thereby reducing methanogenesis (Martin et al., 2010).").

80 Vijn S., *et al.* (2020) *Key Considerations for the Use of Seaweed to Reduce Enteric Methane Emissions from Cattle*. FRONT. VET. SCI. 7(597430): 1–9, 2 ("Feeding livestock many seaweeds—also known as red, green or brown marine macroalgae—has been shown to reduce methane production, but with highly variable results (9–12). For example, *in vitro* analysis suggested that the tropical/subtropical red seaweed *Asparagopsis taxiformis* can reduce methane production by 95% when added to feed at a 5% organic matter inclusion rate... Kinley et al. (14) reported that inclusion of *A. taxiformis* at 0.10 and 0.20% of dietary dry matter over a 90 day period decreased methane production in steers up to 40 and 98%, and produced weight gain improvements of 24 and 17 kg, respectively, relative to control steers."). *See also* Kinley R. D., Martinez-Fernandez G., Matthews M. K., de Nys, R., Magnusson M., Tomkins N. W. (2020) *Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed*, J. CLEAN. PROD. 259(120836): 1–10, 2 ("A rumen *in vitro* study screened 20 different macroalgae species and *Asparagopsis taxiformis* was identified as the primary candidate for further investigation (Machado et al., 2014). Subsequent *in vitro* work to determine optimum inclusion rates for ruminants has demonstrated no negative impact on fermentation with 99% decrease in CH_4 (Kinley et al., 2016a). Validation of the *in vitro* work was demonstrated *in vivo* with a clear inclusion level response effect and decrease of 80% CH_4 production in sheep (Li et al., 2018). Further validation of the capability of *Asparagopsis in vitro* (Roque et al., 2019a; Kinley et al., 2016b) and *in vivo* as a functional feed ingredient for lactating dairy cattle demonstrated CH_4 decrease of 67% (Roque et al., 2019b)."); Abbott D. W., *et al.* (2020) *Seaweed and Seaweed Bioactives for Mitigation of*

Enteric Methane: Challenges and Opportunities, Animals 10(2432): 1–28, 2, 5 (“Recently, researchers concluded that commercial production of the red seaweed A. taxiformis could create new economies due to the fact that addition of small quantities of this seaweed in the diet of ruminant animals reduced CH_4 emissions by up to 98% when included at 0.2% of dry matter intake of steer diets [14].”; “The greatest CH_4 mitigation potential was observed for the red seaweed A. taxiformis with almost complete inhibition in vitro with inclusion levels up to 16.7% of the organic matter (OM). A. taxiformis was highly effective in decreasing the production of CH_4 with a reduction of 99% at doses as low as 2% OM [45,46,47,48].”); *and* Roque B. M., Venegas M., Kinley R. D., de Nys R., Duarte T. L., Yang X., & Kebreab E. (2021) *Red Seaweed (Asparagopsis taxiformis) supplementation reduces enteric methane over 80% in beef steers*, PLoS ONE 16(3): 1–20, 7–9 (“Steers fed low forage TMR and supplemented with *A. taxiformis* reduced CH_4 production, yield, and intensity by 72.4 and 81.9%, 69.8 and 80.0%, and 67.5 and 82.6% for Low and High treatments, respectively. Additionally, H2 production, yield, and intensity increased by 419 and 618%, 503 and 649%, and 566 and 559% for the Low and High treatments, respectively. No significant differences were found in CO_2 production, yield, or intensity in any of the three diets.”).

81 Walsh B. J., Rydzak F., Palazzo A., Kraxner F., Herrero M., Schenk P. M., Ciais P., Janssens I. A., Peñuelas J., Niederl-Schmidinger A., & Obersteiner M. (2015) *New feed sources key to ambitious climate targets*, Carbon Balance Manage. 10(1): 26, 1–8, 1, 2 (“Despite research into microalgae as a next-generation energy source, the land-sparing consequences of alternative sources of livestock feed have been overlooked. Here we use the FeliX model to quantify emissions pathways when microalgae is used as a feedstock to free up to 2 billion hectares of land currently used for pasture and feed crops.”; “Relative to this baseline, we assess the maximum theoretical emissions mitigation potential of microalgae alternately as a source of biomass for energy (*Alg-Fuel*) and as a feedstock (*Alg-Feed*). In these scenarios, we impose exogenously the construction of 25-50 Mha of algaculture at a constant rate between 2015 and 2060.”).

82 McCullogh C. (1 July 2022) *Beef produced with 90% methane reducing feed hits shelves*, All About Feed (“The more environmentally friendly beef is available from June 30 in selected Coop supermarkets in Sweden. It is claimed 5% of the world’s greenhouse gas emissions come from methane produced by cows’ burps and farts.”). *See also* Peters A. (30 June 2022) *The world’s first ‘methane-reduced’ beef is now at grocery stores*, Fast Company (“At the Swedish grocery chain, Coop, there’s now a new product that isn’t available anywhere else in the world: “low methane” beef. Selected stores are selling a limited-edition run of ground beef, sirloin steak, and beef fillets from cattle that have been fed red seaweed—a supplement that cuts emissions of methane, a potent greenhouse gas that cows and steers emit when they burp and fart.”).

83 For example, *see generally* Zhou Y.-M., Liu Y., Liu W., & Shen Y. (2023) *Generation of microbial protein feed (MPF) from waste and its application in aquaculture in China*, J. Environ. Chem. Eng. 11(2): 109297.

84 Pikaar I., Matassa S., Bodirsky B. L., Weindl I., Humpenöder F., Rabaey K., Boon N., Bruschi M., Yuan Z., Van Zanten H., Herrero M., Verstraete W., & Popp A. (2018) *Decoupling Livestock from Land Use through Industrial Feed Production Pathways*, Environ. Sci. Technol. 52(13): 7351–7359, 7351 (“Our analysis reveals that by 2050, MP can replace, depending on socio-economic development and MP production pathways, between 10–19% of conventional crop-based animal feed protein demand.”).

85 Mottet A., de Haan C., Falcucci A., Tempio G., Opio C., & Gerber P. (2017) *Livestock: On our plates or eating at our table? A new analysis of the feed/food debate*, Glob. Food Secur. 14: 1–8, 5 (“Producing cereal grain for livestock uses up a total of 210.5 million ha, or some 31% of the global area devoted to cereal production (FAOSTAT, 2016). The production of cereals for monogastrics occupies 138 million ha, or 20% of the global cereal-growing area. … Total arable land used to feed livestock reaches about 560 million ha, or about 40% of the global arable land.”).

86 Pikaar I., Matassa S., Bodirsky B. L., Weindl I., Humpenöder F., Rabaey K., Boon N., Bruschi M., Yuan Z., Van Zanten H., Herrero M., Verstraete W., & Popp A. (2018) *Decoupling Livestock from Land Use through Industrial Feed Production Pathways*, ENVIRON. SCI. TECHNOL. 52(13): 7351–7359, 7354 ("MP is a limited substitute for the feed components that provide starch or fibers for digestibility. We therefore restrict the replacement of cereals in a way that the resulting share is still consistent with the highest regional estimate of the minimum percentage inclusion of feed ingredients in concentrates for dairy and beef cattle used by Herrero et al. (2013) to harmonize their feed model with FAO commodity balance sheets. Following this conservative approach, we assumed that cereals exceeding 60% of the concentrates in the feed basket for poultry or 70% for other animals can be replaced by MP. Crop residues, forage crops, pasture, molasses and other feed items were assumed to be irreplaceable by MP.").

87 Pikaar I., Matassa S., Bodirsky B. L., Weindl I., Humpenöder F., Rabaey K., Boon N., Bruschi M., Yuan Z., Van Zanten H., Herrero M., Verstraete W., & Popp A. (2018) *Decoupling Livestock from Land Use through Industrial Feed Production Pathways*, ENVIRON. SCI. TECHNOL. 52(13): 7351–7359, 7351 ("As a result, global cropland area, global nitrogen losses from croplands and agricultural greenhouse gas emissions can be decreased by 6% (0–13%), 8% (−3–8%), and 7% (−6–9%), respectively. Interestingly, the technology to industrially produce MP at competitive costs is directly accessible for implementation and has the potential to cause a major structural change in the agro-food system.").

88 de Sousa A. (9 September 2021) *World's Top Beef Supplier Approves Methane-Busting Cow Feed*, BLOOMBERG ("Latin America is the first region to grant approvals for the DSM product, which is also trying to get permission in the European Union, the U.S. and New Zealand. A trial on Brazilian beef showed Bovaer cut methane emissions from cows' stomachs by as much as 55%, the company said. Bovaer has undergone trials in 13 countries, with more than 48 peer-reviewed studies published."). *See also* Bryce E. (30 September 2021) *Kowbucha, seaweed, vaccines: the race to reduce cows' methane emissions*, THE GUARDIAN ("There are dozens more livestock methane interventions under development, according to a recent assessment co-authored by Ermias Kebreab. But only a handful – including Bovaer and Zelp – have reached the market. Even here, there's still fine-tuning to be done. For instance Bovaer needs to be constantly in the rumen to work, meaning it may be less practical for free-ranging cattle whose feeding is less controlled (van Nieuwland said DSM is working to develop slow-release 3-NOP to help with this).").

89 Byrne J. (5 July 2023) *dsm-firmenich: Bovaer has saved 50,000 tons of CO2e to date, FEED NAVIGATOR* ("Authorities recently approved the sale of Bovaer in Paraguay, for use in dairy and beef cattle, making it the seventh country in Latin America to give the feed additives the green light, while Elanco Animal Health, dsm-firmenich's strategic partner for developing, manufacturing, and commercializing Bovaer in the US, anticipates US approval and launch of the supplement in the first half of 2024."). *See also* de Sousa A. (9 September 2021) *World's Top Beef Supplier Approves Methane-Busting Cow Feed*, BLOOMBERG ("Latin America is the first region to grant approvals for the DSM product, which is also trying to get permission in the European Union, the U.S. and New Zealand. A trial on Brazilian beef showed Bovaer cut methane emissions from cows' stomachs by as much as 55%, the company said. Bovaer has undergone trials in 13 countries, with more than 48 peer-reviewed studies published."); *and* Bryce E. (30 September 2021) *Kowbucha, seaweed, vaccines: the race to reduce cows' methane emissions*, The Guardian ("There are dozens more livestock methane interventions under development, according to a recent assessment co-authored by Ermias Kebreab. But only a handful – including Bovaer and Zelp – have reached the market. Even here, there's still fine-tuning to be done. For instance Bovaer needs to be constantly in the rumen to work, meaning it may be less practical for free-ranging cattle whose feeding is less controlled (van Nieuwland said DSM is working to develop slow-release 3-NOP to help with this).").

90 *See generally* Steele M. (22 June 2023) *Methane-reducing supplement for cows still trapped in regulatory limbo*, RADIO NEW ZEALAND.

91 European Commission (23 February 2022) Daily News 23/02/2022, Press Release ("Today, Member States have approved the marketing in the EU of an innovative feed additive, as proposed by the Commission. The additive, consisting of 3-nitrooxypropanol, will help to reduce the emission of methane, a potent greenhouse gas, from cows. Commissioner for Health and Food Safety, Stella Kyriakides, said: "Innovation is key for a successful shift towards a more sustainable food system. The EU continues to lead the way in ensuring food safety while adapting to new technologies that can make food production more sustainable. Cutting farming-related methane emissions is key in our fight against climate change and today's approval is a very telling example of what we can achieve through new agricultural innovations." The product went through a stringent scientific assessment by the European Food Safety Authority which concluded that it is efficacious in reducing methane emissions by cows for milk production. Once the decision is adopted by the Commission, expected in the coming months, the feed additive will be the first of its kind available on the EU market."). *See also* Martin R. (20 April 2022) *Methane-reducing feed pilot to include 10,000 cows in three European countries*, IRISH EXAMINER ("The cooperative is set to pilot the use of Bovaer® with 10,000 dairy cows across more than 50 farms in Denmark, Sweden and Germany, ensuring a diverse group of farms participate in the pilot programme. . . If preliminary findings are as expected, Arla Foods plans to double the pilot project to include 20,000 cows in 2023. Bovaer® is currently commercially available in the EU, Brazil, Chile, and Australia.").

92 Caro D., Kebreab E., & Mitloehner F. M. (2016) *Mitigation of enteric methane emissions from global livestock systems through nutrition strategies*, CLIMATIC CHANGE 137(3–4): 467–480, 477 ("This study shows a global reduction of 104 $MtCO_2eq$ released from dairy cattle through the supplementation of traditional diets with lipids. The changes proposed imply a transition toward a diet with a lower share of crop residues, and a lower dependence on extensive and non–managed grasslands."). *See also* Gerber P. J., *et al.* (2013) *Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review*, ANIMAL 7: 220–234, 224 ("On the basis of several studies (Eugene et al., 2008; Grainger and Beauchemin 2011; Rabiee et al., 2012), Hristov et al. (2013) conclude that lipids are effective in reducing enteric CH_4 emission, but the feasibility of this mitigation practice depends on affordability of oil products and potential negative effects on animal productivity, for example, reduction in fibre digestibility.").

93 Kozicka M., Havlík P., Valin H., Wollenberg E., Deppermann A., Leclère D., Lauri P., Moses R., Boere E., Frank S., Davis C., Park E., & Gurwick N. (2023) *Feeding climate and biodiversity goals with novel plant-based meat and milk alternatives*, NAT. COMMUN. 14(1): 5316, 1–13, 6 ("We show that substituting 50% of ASF with novel alternatives can lead to profound system-wide impacts. Unlike previous studies that assessed dietary changes with novel foods, in this study we considered a more realistic composition of the plant ingredients that would be used to produce novel alternatives and analyzed them in a dynamic systemwide global framework. Instead of growing by 15% in the REF scenario, agriculture and land use emissions decline by 31%. A large part of this decline comes from CH_4 reduction, which could have significant nearterm climate mitigation benefits[59]. The result is comparable in relative terms to a previous analysis of replacing 60% of beef consumption in the USA with plant-based alternatives, which found agricultural emissions reduction in the USA by 13.5%[40].").

94 Aykan N. F. (2015) *Red meat and colorectal cancer*, ONCOL. REV. 9(288): 38–34, 38, 41 ("Colorectal cancer (CRC) is the third most common cancer in men and the second in women worldwide. More than half of cases occur in more developed countries. The consumption of red meat (beef, pork, lamb, veal, mutton) is high in developed countries and accumulated evidence until today demonstrated a convincing association between the intake of red meat and especially processed meat and CRC risk."; "Experimental studies about promotion of carcinogenesis by high total fat intake from meat were shown inconsistent results and epidemiological studies failed to confirm a link.[26] But, some positive reports may be partly explained by high saturated fat intake. Fatty diets favor obesity which in turn increases insulin resistance, thus promote tumor growth.[41]"). *See also* Romanello M., *et al*. (2023) *The*

2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms, The Lancet, 1–49, 27 ("[A]n excess consumption of dairy and red and processed meat, which contributed to 57% of agricultural emissions (indicator 3.3.1), was responsible for 16% of all diet-related deaths (1·9 million). Very high HDI countries experienced the highest diet-related death rate (deaths per 100 000), 2·4-times higher than the rate in low HDI countries. The very high HDI group also had the highest death rate related to excess dairy and red and processed meat consumption, 6·7-times higher than the average mortality for countries in other HDI groups (figure 9).").

95 Good Food Institute, *Alternative proteins can help prevent the next pandemic* (*last visited* 3 October 2023) ("Alternative proteins do not require antibiotics for their production and therefore will not contribute to the proliferation of antibiotic-resistant microorganisms. This is critically important to public health. In the United States, more than 70 percent of medically important antibiotics needed to treat humans are used in intensive meat production to foster animal growth and prevent illness.[1]").

96 *See* Table: Summarizing plant-based food market sales data *in* Ignaszewski E. & Piece B. (2023) *U.S. retail market insights for the plant-based industry*, Good Food Institute.

97 *See generally* Good Food Institute (2022) 2022 State of the Industry Report: *Cultivated meat and seafood.*

98 Kebreab E., & Feng X. (2021) *Strategies to Reduce Methane Emissions from Enteric and Lagoon Sources*, California Air Resources Board, 69 ("In general, higher moisture contents in raw composting manure could enhance the CH_4 mitigation rates, however, the pH, and C/N content were not linearly related to CH_4 mitigation. Adding biochar, acids, and straw to manure could mitigate CH_4 emissions by 82.4%, 78.1%, and 47.7%, respectively. However, the data for straw is quite small so it should not be taken out of context as it may introduce a source of carbon into lagoons. The meta-analysis conducted with selected additives indicated manure additives were an effective method to reduce CH_4 emission, with biochar being the most effective. However, further studies of manure additives on CH_4 mitigation are required to support a more accurate quantitative analysis and potential impacts to water quality and crop yield after land application. Most of the research for biochar and straw is when used as additive to solid or semi solid manure so theys should be interpreted in that context."). *See also* Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, White Paper, 26 ("Another emerging option involves adding acid to manure stored in wet form, which can almost eliminate methane emissions. Some experiments with acidification have occurred for many years (Fangueiro, Hjorth, and Gioelli 2015) (Søren O. Petersen, Andersen, and Eriksen 2012), but experimental work has been increasing (Rodhe et al. 2019). Acidification can be done at different stages of manure management: in the barn, in storage tanks, prior to field application. Methane reductions require a regular, but modest, insertion of acid into storage tanks. Acidifying manure also reduces ammonia losses when methane is applied, and in some experiments increases yields (Loide 2019). Yield gains probably occur if farmers either do not apply or are not allowed to apply more nitrogen fertilizer to replace the nitrogen lost with the releases of ammonia. The amount of acid required for sufficient acidification to greatly reduce methane is still unclear."; "There are also a variety of promising innovative methods to reduce methane. There is experimental evidence, for example, that some additives, such as sulfate, can be added in modest quantities and still reduce two-thirds of the methane emissions from storage even without significantly reducing pH (Petersen, Andersen & Eriksen 2012) (Petersen et al. 2014) (Sokolov et al. 2020)."); Peterson C., El Mashad H. M., Zhao Y., Pan Y., & Mitloehner F. M. (2020) *Effects of SOP Lagoon Additive on Gaseous Emissions from Stored Liquid Dairy Manure*, Sustainability 12(1393): 1–17, 1 ("A variety of additives have been applied to reduce emissions from manure. Although the composition and mechanism of the emission reduction of several additives are known, information on many other commercial additives is not available because of confidentiality and limits in the marketing literature. Calcium sulfate (gypsum)

can be found abundantly in nature and has been used to improve soil properties. . . . Different forms of gypsum have been tested for the mitigation of GHG and ammonia emissions from livestock effluents. The results have had varying results: while some studies reported a decrease in ammonia emissions after the addition of gypsum, not all have demonstrated the efficacy of gypsum in reducing the release of GHGs. Many of the results were obtained using a considerable amount of material (3% to 10% of manure wet weight) making the application not practical in real-world conditions. Borgonovo et al. first published results on this specific commercial additive (SOP LAGOON), made of gypsum processed with proprietary technology, and found that the addition of the products to fresh liquid manure has a reduction potential of 21.5% of CH_4, 22.9% of CO_2, 100% of N_2O and 100% of NH3 emissions on day 4, even at very low dosages. It should be mentioned that similar to other commercial additives, the exact manufacturing process of SOP Lagoon is unknown due to confidentiality."); *and* Borgonovo F., Conti C., Lovarelli D., Ferrante V., & Guarino M. (2019) *Improving the sustainability of dairy slurry with a commercial additive treatment*, SUSTAINABILITY 11(4988): 1–14, 8 ("N_2O, CO_2, and CH_4 emissions, from the treated slurry, were respectively 100%, 22.9% and 21.5% lower than the control at T4 when the emission peaks were recorded.").

99 Chiodini M. E., Costantini M., Zoli M., Bacenetti J., Aspesi D., Poggianella L., & Acutis M. (2023) *Real-Scale Study on Methane and Carbon Dioxide Emission Reduction from Dairy Liquid Manure with the Commercial Additive SOP LAGOON*, Sustainability 15(1803): 1–13, 1 ("After 3 and 4 months from the first additive applications, the SL storage tank showed lower and statistically significantly different emissions concerning the UNT (up to −80% for CH_4 and −75% for CO_2, $p < 0.001$), confirming and showing improved results from those reported in the previous small-scale works.").

100 Babiker M., *et al.* (2022) *Chapter 12: Cross Sectoral Perspectives* in CLIMATE CHANGE 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., *et al.* (eds.), 12-102 ("Anaerobic digestion of organic wastes (e.g., food waste, manure) produces a nutrient-rich digestate and biogas that can be utilised for heating and cooking or upgraded for use in electricity generation, industrial processes, or as transportation fuel (See Chapter 6) (Parsaee et al. 2019; Hamelin et al. 2021).").

101 Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, White Paper, 24, 25 ("Much of the focus on manure management has been to encourage the use of digesters. Digesters turn even more of the [manure] into methane into biogas, but in a way that can be captured and burned for energy. Millions of small, low-technology digesters are in use in Asia for household energy use, and larger, modern digesters have also received significant investments in Western countries. For farms that now produce large quantities of methane – for example, that use large lagoons to store manure in warm parts of the world – digesters can be a cost-effective mechanism for reducing methane as well as overall greenhouse gas emissions (Searchinger et al. 2019). In other contexts, however, the climate benefits for methane are uncertain and probably unable to justify the expense. The purpose of a digester is to turn as much of the biomass in manure into methane as possible. As a result, digesters create more methane than normal storage systems. Although the intent is to capture and burn this methane for energy, if the digester has significant leakage rates the amount of methane released can exceed the methane released by present management, depending on the system in use. That seems particularly likely in informal, household systems studied so far (Bruun et al. 2014), although the leakage rates around the world have been little studied."; "Several alternative manure management options exist. One starts with more quickly removing manure from barns because barn temperatures tend to be high, and higher temperatures increase methane formation (Montes et al. 2013). Barn storage can lead to high methane losses even in a few days, particularly in pig barns where temperatures are often higher than outside (Petersen et al. 2016). In many systems, it is common for manure to remain in pig or dairy barns for a few weeks – and some for much longer – but it is possible to construct systems and sometimes to operate

existing barns to remove manure each day. One analysis of different studies found average reduction rates for methane at the level of 50%, although that will obviously depend on climate and alternative management systems (Mohankumar, et al. 2018). A second set of options focuses on separating the solid portion of manure from the liquid portion. Even without adding water for barn cleaning, manure in pork and cattle systems tends to be wet enough to create the oxygen-less conditions that create methane. A variety of techniques with increasing sophistication can separate solids from liquids."). *See also* Cameron K. C. & Di H. J. (2019) *A new method to treat farm dairy effluent to produce clarified water for recycling and to reduce environmental risks from the land application of effluent*, J. Soils Sediments 19(5): 2290–2302, 2291 ("The basis of the new method for treating FDE is to use a coagulant to coagulate and flocculate colloidal particles in the FDE into flocs that have sufficient mass for gravity to cause them to settle out of the liquid, thus producing: (i) clarified water and (ii) treated effluent. Coagulation involves the addition of a coagulant to neutralize the negative electrical charges on the surfaces of colloids (e.g. soil, dung, organic matter) that would normally prevent them from coagulating into flocs that have sufficient mass to settle out of the water under gravity. In addition, during mixing of the coagulant into the effluent, the coagulant can create a mechanism called 'sweep floc' which also causes the colloids to stick together producing flocs."); *discussed in* Mulhollem J. (11 July 2022) *Researcher gets grant to study biofilters to reduce livestock facility methane*, The Pennsylvania State University.

102 Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, White Paper, 25 ("Several alternative manure management options exist. One starts with more quickly removing manure from barns because barn temperatures tend to be high, and higher temperatures increase methane formation (Montes et al. 2013). Barn storage can lead to high methane losses even in a few days, particularly in pig barns where temperatures are often higher than outside (Petersen et al. 2016). In many systems, it is common for manure to remain in pig or dairy barns for a few weeks – and some for much longer -- but it is possible to construct systems and sometimes to operate existing barns to remove manure each day. One analysis of different studies found average reduction rates for methane at the level of 50%, although that will obviously depend on climate and alternative management systems (Mohankumar, et al. 2018). A second set of options focuses on separating the solid portion of manure from the liquid portion. Even without adding water for barn cleaning, manure in pork and cattle systems tends to be wet enough to create the oxygen-less conditions that create methane. A variety of techniques with increasing sophistication can separate solids from liquids."). *See also* Cameron K. C., & Di H. J. (2019) *A new method to treat farm dairy effluent to produce clarified water for recycling and to reduce environmental risks from the land application of effluent*, J. Soils Sediments 19(5): 2290–2302, 2291 ("The basis of the new method for treating FDE is to use a coagulant to coagulate and flocculate colloidal particles in the FDE into flocs that have sufficient mass for gravity to cause them to settle out of the liquid, thus producing: (i) clarified water and (ii) treated effluent. Coagulation involves the addition of a coagulant to neutralize the negative electrical charges on the surfaces of colloids (e.g. soil, dung, organic matter) that would normally prevent them from coagulating into flocs that have sufficient mass to settle out of the water under gravity. In addition, during mixing of the coagulant into the effluent, the coagulant can create a mechanism called 'sweep floc' which also causes the colloids to stick together producing flocs."); *discussed* in Mulhollem J. (11 July 2022) *Researcher gets grant to study biofilters to reduce livestock facility methane*, The Pennsylvania State University.

103 Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, White Paper, 24, 25 ("Much of the focus on manure management has been to encourage the use of digesters. Digesters turn even more of the [manure] into methane into biogas, but in a way that can be captured and burned for energy. Millions of small, low-technology digesters are in use in Asia for household energy use, and larger, modern digesters have also received

significant investments in Western countries. For farms that now produce large quantities of methane – for example, that use large lagoons to store manure in warm parts of the world – digesters can be a cost-effective mechanism for reducing methane as well as overall greenhouse gas emissions (Searchinger et al. 2019). In other contexts, however, the climate benefits for methane are uncertain and probably unable to justify the expense. The purpose of a digester is to turn as much of the biomass in manure into methane as possible. As a result, digesters create more methane than normal storage systems. Although the intent is to capture and burn this methane for energy, if the digester has significant leakage rates the amount of methane released can exceed the methane released by present management, depending on the system in use. That seems particularly likely in informal, household systems studied so far (Bruun et al. 2014), although the leakage rates around the world have been little studied."; "Several alternative manure management options exist. One starts with more quickly removing manure from barns because barn temperatures tend to be high, and higher temperatures increase methane formation (Montes et al. 2013). Barn storage can lead to high methane losses even in a few days, particularly in pig barns where temperatures are often higher than outside (Petersen et al. 2016). In many systems, it is common for manure to remain in pig or dairy barns for a few weeks – and some for much longer – but it is possible to construct systems and sometimes to operate existing barns to remove manure each day. One analysis of different studies found average reduction rates for methane at the level of 50%, although that will obviously depend on climate and alternative management systems (Mohankumar, et al. 2018). A second set of options focuses on separating the solid portion of manure from the liquid portion. Even without adding water for barn cleaning, manure in pork and cattle systems tends to be wet enough to create the oxygen-less conditions that create methane. A variety of techniques with increasing sophistication can separate solids from liquids."). *See also* Cameron K. C., & Di H. J. (2019) *A new method to treat farm dairy effluent to produce clarified water for recycling and to reduce environmental risks from the land application of effluent*, J. Soils Sediments 19(5): 2290–2302, 2291 ("The basis of the new method for treating FDE is to use a coagulant to coagulate and flocculate colloidal particles in the FDE into flocs that have sufficient mass for gravity to cause them to settle out of the liquid, thus producing: (i) clarified water and (ii) treated effluent. Coagulation involves the addition of a coagulant to neutralize the negative electrical charges on the surfaces of colloids (e.g. soil, dung, organic matter) that would normally prevent them from coagulating into flocs that have sufficient mass to settle out of the water under gravity. In addition, during mixing of the coagulant into the effluent, the coagulant can create a mechanism called 'sweep floc' which also causes the colloids to stick together producing flocs."); *discussed in* Mulhollem J. (11 July 2022) *Researcher gets grant to study biofilters to reduce livestock facility methane*, The Pennsylvania State University.

104 Mayberry D., Ash A., Prestwidge D., Godde C. M., Henderson B., Duncan A., Blummel M., Ramana Reddy Y., & Herrero M. (2017) *Yield gap analyses to estimate attainable bovine milk yields and evaluate options to increase production in Ethiopia and India*, Agric. Syst. 155: 43–51, 43 ("We tested interventions based on improved livestock nutrition and genetics in the extensive lowland grazing zone and highland mixed crop-livestock zones of Ethiopia, and the intensive irrigated and rainfed zones of India. Our analyses indicate that there are considerable yield gaps for dairy production in both countries, and opportunities to increase production using the interventions tested. In some cases, combined interventions could increase production past currently attainable livestock yields."); *see generally* Dzanku F. M., Jirström M., & Marstorp H. (2015) *Yield Gap-Based Poverty Gaps in Rural Sub-Saharan Africa*, World Development 67: 336–62; *and* Nin-Pratt A., Johnson M., Magalhes E., You L., Diao X., & Chamberlin J. (2011) Yield gaps and potential agricultural growth in West and Central Africa, International Food Policy Research Institute.

105 Herrero M., Henderson B., Havlík P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. N., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, Nat. Clim. Change 6(5): 452–461, 455 ("It may be possible

in some regions to rebalance the distribution of inputs to optimize production and close yield gaps[63,64]. The benefits and impacts of irrigation and the water needed for crop production vary greatly across the globe, but addressing these imbalances could bring yields to within 95% of their current potential for 16 important food and feed crops, and adding 2.3 billion tonnes (5 × 10^{15} kcal) of new production (a 58% increase)[63]. Closing the yield gap of the same crops to 75% of their potential could increase global production by 1.1 billion tonnes (2.8 × 10^{15} kcal), an increase of 28% (ref. 63).").

106 Herrero M., Henderson B., Havlík P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. N., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, Nat. Clim. Change 6(5): 452–461, 454 ("Many parts of the developing world have high emissions from livestock, which are produced at high emissions intensities due to low productivity and large numbers of animals (for example, parts of Africa and Latin America)[13].").

107 Gerber P. J., Steinfeld H., Henderson B., Mottet A., Opio C., Dijkman J., Falcucci A., & Tempio G. (2013) *Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities*, Food and Agriculture Organization of the United Nations: Rome, 42, 57 ("In ruminant production, there is a strong relationship between productivity and emission intensity – up to a relatively high level of productivity, emission intensity decreases as yield increases."; "Mitigation is achievable in these areas but should be considered in view of food security and climate change adaptation concerns. Even modest productivity improvements in ruminant systems and improved grazing practices could yield substantial gains in both emission intensities and food security."); *See generally* Herrero M., Henderson B., Havlík P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. N., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, Nat. Clim. Change 6(5): 452–61.

108 McGrath S. R., Thomas D. T., & Greer A. W. (2021) *Dual-purpose cropping: the opportunity for a step change in production in the temperate region of Australia*, Anim. Prod. Sci. 61(11): i–iv, i ("Dual-purpose cropping refers to the establishment of annual crops such as cereals (e.g. wheat, barley, oats and triticale) and brassicas (mainly canola) with the intended purpose of grazing during the vegetative stage and harvesting grain after the crop matures. Twelve years ago, a special issue published in Animal Production Science reported key studies from Grain and Graze, a research and extension program which provided impetus for increased uptake of dual-purpose cropping and highlighted management of crops and livestock to optimise production.").

109 Thornton P. K., & Herrero M. (2010) *Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics*, Proc. Natl. Acad. Sci. 107(46): 19667–19672, 19668 (*see* Table 1: Mitigation options evaluated for adoption rates of different practices).

110 Bryan E., Ringler C., Okoba B., Koo J., Herrero M., & Silvestri S. (2013) *Can agriculture support climate change adaptation, greenhouse gas mitigation and rural livelihoods? insights from Kenya*, Climatic Change 118(2): 151–165, 162 ("Promoting the adoption of triple-win strategies will be a major challenge. The extensive literature on constraints to the adoption of agricultural technologies and practices shows that there are several factors that impede uptake, such as lack of information, risk aversion, lack of access to input and output markets, and lack of financial incentives (Barrett et al. 2002; Ehui and Pender 2005; Lee 2005; Herrero et al. 2010b; McDermott et al. 2010). Overcoming these obstacles will require targeted investments to make smallholder systems more market-oriented (Herrero et al. 2010b; McDermott et al. 2010). Indeed, farmers in Kenya with access to input and output markets have been shown to have higher use of inputs, such as fertilizer, and greater productivity (Owuor 1999; Strasberg et al. 1999). Strengthening the quality and delivery of information services is also critical, particularly because triple-win strategies are location-specific (based on the local agroecology, climate factors, soil charateristics, livelihood systems, socio-economic conditions, etc.) as this article and many others have shown (Solano et al. 2000; Ehui and Pender 2005; Lee 2005; Kato et al. 2011; Silvestri et al. 2012).").

111 Aker J. C. (2011) *Dial "A" for agriculture: a review of information and communication technologies for agricultural extension in developing countries*, Agricultural Economics 42(6): 631-647, 632 ("Mobile phones significantly reduce communication and information costs for the rural poor. This not only provides new opportunities for rural farmers to obtain access to information on agricultural technologies, but also to use ICTs in agricultural extension services."); Cole S. A., & Fernando A. (2020) *'Mobile'izing Agricultural Advice: Technology Adoption, Diffusion, and Sustainability*, Harvard Business School Finance Working Paper No. 13-047, ("A two year study evaluates an innovative voice-based ICT advisory service for smallholder cotton farmers in India, demonstrating significant demand for, and trust in, new information. Farmers substantially alter their sources of information and consistently adopt inputs for cotton farming recommended by the service.")

112 Fabregas R., Kremer M., Lowes M., On R., & Giulia Zane . (2024) *Digital Information Provision and Behavior Change: Lessons from Six Experiments in East Africa*, NBER Working Paper No. 32048. ("Combining the effects of all six programs in a meta-analysis using odds ratios, a relative measure of effects that is less sensitive to variations in baseline input adoption probabilities, we find a small but statistically significant effect on following the recommendations (OR: 1.22, 95% CI 1.16 to 1.29, N=6). The aggregate effect for following recommendations about a newly introduced technology (agricultural lime) is 1.19 (95% CI 1.11 to 1.27, N=6), whereas the effect for following recommendations for largely unused types of a well-known technology (chemical fertilizers) is 1.27 (95% CI: 1.15 to 1.40, N=4).")

113 *See Table 5* Cole S., & Sharma G. (2017) *The Promise and Challenges in Implementing ICT for Agriculture*.

114 Jeffrie N., Bahia K., Carboni I., Lindsey D., Sibthorpe C., & Zagdanski J. (2023) *The Mobile Gender Gap Report 2023*, GSMA: 1-70, 31. ("61% of women in LMICs now use mobile internet compared to 75% of men (see Figure 9).")

115 *See generally* MoooFarm, Solution (*last visited* 27 November 2023).

116 *See generally* Bang R. N., Guajardo M., & Hansen B. G. (2023) *Recent advances in decision support for beef and dairy farming: modeling approaches and opportunities*, Int. Trans. Operational Res. 30(6): 2807–2839. *See also* International Livestock Research Institute, & Center for Supporting Evidence-Based Interventions in Livestock (17 May 2022) *A snapshot of digital tools for livestock development*, Livestock Data For Decisions; *and* University of Wisconsin-Madison Animal & Dairy Sciences Extension, Tools (*last visited* 27 November 2023).

117 For an example of advantages to Tier II model estimates of methane intensity, *see generally* Jo N., Kim J., & Seo S. (2016) *Comparison of models for estimating methane emission factor for enteric fermentation of growing-finishing Hanwoo steers*, SpringerPlus 5(1): 1212.

118 Conrad H. R., Pratt A. D., & Hibbs J. W. (1964) *Regulation of Feed Intake in Dairy Cows. I. Change in Importance of Physical and Physiological Factors with Increasing Digestibility*, J. Dairy Sci. 47(1): 54–62, 60 ("After adjusting for productive energy and body size by covariance, the relationship of total dry matter intake to digestibility is shown in the right side of Figure 4 for cows on the high-roughage rations adjusted to two levels of milk production. The mean adjusted dry matter intake declined more sharply in the cows fed the higher grain ration; that is, corn silage with hay as indicated by a larger negative exponent for D, -1.19 compared to -0.46, in the regression equation, Table 5. Because digestibility is inversely proportional to total dry matter intake, the value obtained from empirical calculations, that is, digestibility raised to -1.00 power, is intermediate between the results observed for the high-roughage and the higher grain ration. The empirical calculation assumes a constant level of digestible nutrient intake.").

119 Thornton P. K. & Herrero M. (2010) *Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics*, Proc. Natl. Acad. Sci. 107(46): 19667–19672, 19667 ("The impacts of adoption of improved pastures, intensifying ruminant diets, changes in

land-use practices, and changing breeds of large ruminants on the production of methane and carbon dioxide are calculated for two levels of adoption: complete adoption, to estimate the upper limit to reductions in these greenhouse gases (GHGs), and optimistic but plausible adoption rates taken from the literature, where these exist. Results are expressed both in GHG per ton of livestock product and in GtCO$_2$-eq. We estimate that the maximum mitigation potential of these options in the land-based livestock systems in the tropics amounts to approximately 7% of the global agricultural mitigation potential to 2030. Using historical adoption rates from the literature, the plausible mitigation potential of these options could contribute approximately 4% of global agricultural GHG mitigation. This could be worth on the order of $1.3 billion per year at a price of $20 per t CO$_2$-eq.").

120 Herrero M., Grace D., Njuki J., Johnson N., Enahoro D., Silvestri S., & Rufino M. C. (2013) *The roles of livestock in developing countries*, ANIMAL 7: 3–18, 12 ("Intensifying livestock production requires using additional nutrients to produce feeds. Nitrogen fixing legumes play a very important role in the developed world dairy industry, with soya beans produced in South America and the United States being fed as protein supplements in Europe. Research in the developing world has tried to implement this model of using legumes produced on farm on a local scale in, for example, African mixed systems with some success (Sumberg, 2002), but not enough to supply the future demand for feeds. Producing grain legumes or fodder legumes requires in certain soils the addition of P fertilisers, and there are GHG emissions associated with their production. Dual-purpose legumes such as cowpea may be used as food and feeds, and its production justified to contribute to income and nutrition (Singh *et al.,* 2003). However, the production of feeds, including legumes, results in emissions to the environment (e.g. Chikowo *et al.*, 2004; Baggs *et al.,* 2006) that must be accounted for by the livestock sector. Designing technologies for intensification requires in the developing world addressing the trade-off poverty reduction and environmental impact.").

121 Smith P., *et al.* (2013) *How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals?*, GLOB. CHANGE BIO. 19(8): 2285–2302, 2292 ("In this review, we do not attempt to address all aspects of food security; rather we focus on those aspects of food security that interface with greenhouse gas mitigation in agriculture. Historical expansion of agriculture into forests and natural ecosystems (Bruinsma, 2003) has contributed significantly to the loss of what we now refer to as ecosystem services (Costanza *et al*., 1997). Because many ecosystem services are lost on such conversion, it is apparent that future increases in food supply need to be met without large increases in agricultural area, i.e. to derive more agricultural products from the same area (Godfray *et al.*, 2010; Smith *et al.*, 2010; Smith, 2012b)."); *and* Herrero M., Henderson B., Havlík P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. N., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, NAT. CLIM. CHANGE 6(5): 452–61, 452 ("Although intensification has occurred in some regions, agricultural land expansion has also been an important component of production growth in places such as Africa and Latin America. These trends, if continued, could drive significant increases in greenhouse gas (GHG) emissions, deforestation, loss of biodiversity and other negative impacts on the environment7.").

122 Thornton P. K. & Herrero M. (2010) *Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics*, PROC. NATL. ACAD. SCI. 107(46): 19667–19672, 19667 ("Results also are shown for the amount of CO$_2$ equivalent (CO$_2$-eq) mitigated in relation to the three pathways considered, where these come into play for the different options: a reduction in livestock numbers associated with diet improvement, the carbon sequestered via restoration of degraded range-lands, and the extra carbon sequestered as a result of land-use change, expressed as Mt CO$_2$-eq.").

123 Herrero M., Henderson B., Havlík P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. N., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse*

gas mitigation potentials in the livestock sector, NAT. CLIM. CHANGE 6(5): 452–61, 452 ("Although intensification has occurred in some regions, agricultural land expansion has also been an important component of production growth in places such as Africa and Latin America. These trends, if continued, could drive significant increases in greenhouse gas (GHG) emissions, deforestation, loss of biodiversity and other negative impacts on the environment[7].").

124 Gonzalez-Fischer C., & Herrero M. (2023) *Net greenhouse gas mitigation in the livestock sector requires a reduction in animal numbers* (PNAS, under review).

125 Frank S., Beach R., Havlík P., Valin H., Herrero M., Mosnier A., Hasegawa T., Creason J., Ragnauth S., & Obersteiner M. (2018) *Structural change as a key component for agricultural non-CO2 mitigation efforts*, NAT. COMMUN. 9(1): 1060, 1–8, 4 ("Adoption of these technical options would require investment and operation costs of around 13 bn $/year globally by 2050 (12 bn $ in 2030), the majority arising in emerging and developing regions like Asia (almost half) or Sub-Saharan Africa (10%) while only one quarter of the costs occur in developed countries (Europe, Oceania, and North America). Structural adjustments, i.e., shift from rather GHG inefficient extensive grazing systems toward mixed grass–cereal feeding systems, and could contribute 1.0 $GtCO_2eq$/year and consumer response to prices will add another 0.6 $GtCO_2eq$/year at 100 $/$tCO_2eq$ in 2050."). *See also* Havlík P., Valin H., Herrero M., Obersteiner M., Schmid E., Rufino M. C., Mosnier A., Thornton P. K., Böttcher H., Conant R. T., Frank S., Fritz S., Fuss S., Kraxner F. & Notenbaert A. (2014) *Climate change mitigation through livestock system transitions*, PROC. NATL. ACAD. SCI. 111(10): 3709–3714, 3709 ("We find that even within existing systems, autonomous transitions from extensive to more productive systems would decrease GHG emissions and improve food availability. Most effective climate policies involving livestock would be those targeting emissions from land-use change.").

126 Thornton P. K. & Herrero M. (2010) *Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics*, PROC. NATL. ACAD. SCI. 107(46): 19667–19672, 19668 (*see* Table 1 for examples of livestock management options that increase animal productivity and reduce emissions).

127 Thornton P. K. & Herrero M. (2010) *Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics*, PROC. NATL. ACAD. SCI. 107(46): 19667–19672, 19669 ("Next is the agroforestry option, which sequesters carbon and intensifies diet quality to reduce animal numbers. Improvements in the use of improved pastures and crop residue digestibility have the next-highest mitigation potentials owing to their broad recommendation domains and the marginal reductions in CH_4 production per unit of output that can be obtained.").

128 Gill M., Smith P., & Wilkinson J. M. (2010) *Mitigating climate change: the role of domestic livestock*, ANIMAL 4(3): 323–333, 328 ("Such research needs to adopt a systems approach, however, since Hindrichsen et al. (2006) reported a negative correlation between enteric methane production v. methane released from the slurry of cows offered forage-only diets compared to those offered forage supplemented with concentrates. The potential benefits to the cattle and sheep industries globally of finding a compound that would reduce methane production without decreasing productivity or increasing methane and N_2O emissions from manure and that could be applied in pastoral systems with low labour inputs are huge. The challenge is that ruminants evolved 40 million years ago with a pre-gastric digestion system to enable them to feed on cellulose, with methane produced as a by-product (see e.g. Van Soest (1994)) and there is no advantage per se to that ecosystem of avoiding methane production.").

129 Herrero M., Havlík P., Valin H., Notenbaert A., Rufino M. C., Thornton P. K., Blümmel M., Weiss F., Grace D., & Obersteiner M. (2013) *Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems*, PROC. NATL. ACAD. SCI. 110(52): 20888–20893, 20892 ("We estimate that grass accounts for close to 50% of feed use in livestock systems and that it is a crucial feed resource for both grazing and mixed production systems. At the same time, grasslands are

sometimes considered either underused or seen as an ecosystem warranting judicious management because of their importance for protecting key regulating ecosystems services (carbon, biodiversity, water) (1, 5, 29). The importance of this finding lies in the impacts that the increasing demand for livestock products might have on grassland ecosystems. Grasslands are often at the epicentre of land-use change processes (43): conversion into grassland is a primary cause of deforestation; afforestation for carbon sequestration or biofuel production occurs in grassland areas that have previously been cleared; pasture intensification to increase productivity, incomes, and mitigate GHG is occurring in several parts of the world; at the same time, rangeland degradation because of overgrazing and land subdivision occurs in other parts of the world; yet grasslands sustain the livelihoods of large numbers of vulnerable people in many parts of the world. Detailed studies on the role and fate of grasslands as a multifunctional resource require urgent attention.”).

130 Gill M., Smith P., & Wilkinson J. M. (2010) *Mitigating climate change: the role of domestic livestock*, Animal 4(3): 323–333, 323 (“Improving efficiency of livestock production through better breeding, health interventions or improving fertility can also decrease GHG emissions through decreasing the number of livestock required per unit product. Increasing the energy density of the diet has a dual effect, decreasing both direct emissions and the numbers of livestock per unit product, but, as the demands for food increase in response to increasing human population and a better diet in some developing countries, there is increasing competition for land for food v. energy-dense feed crops.”).

131 Van Zanten H. H. E., Herrero M., Van Hal O., Röös E., Muller A., Garnett T., Gerber P. J., Schader C., & De Boer I. J. M. (2018) *Defining a land boundary for sustainable livestock consumption*, Glob. Change Biol. 24(9): 4185–94, 4186–4187 (“The increase in the global supply of animal proteins, from an average of 17 g per person per day in 1960 to 27 g per person per day in 2013 (FAOSTAT, 2017; Supporting information Appendix S1), has increased this so-called feed–food competition (Wilkinson & Lee, 2017). Globally, monogastric animals (e.g., pigs and poultry) consume on average about 2 kg of human-edible feed protein to produce one kg of edible protein (Mottet et al., 2017) and, therefore they consume more human-edible protein than they produce. In a world with a growing population and finite land, their role in human food security, therefore, is open to challenge.”).

132 Herrero M., Henderson B., Havlík P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. N., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, Nat. Clim. Change 6(5): 452–61, 455 (“However, good grassland management can potentially reverse historical soil carbon losses and sequester substantial amounts of carbon in grazing-land soils (Fig. 4a). Much of this sequestration potential may be economically feasible, because it can be realized by implementing practices that enhance forage production[41]. Changes in grazing management — increasing or reducing the forage consumption rate to maximize forage production — could lead to annual sequestration of up to 150 MtCO$_2$e yr–^{1} in the world›s grazing lands[56] (Fig. 4b). Much of this potential (81%, approximately 120 MtCO$_2$e yr^{-1}) is in developing countries, occurring in areas where production is predicted to increase following a period of de-stocking, that is, in areas where primary production can recover from overgrazing[56]. The use of legumes in pastures has been estimated to sequester 200 MtCO$_2$e yr^{-1} globally, though this could increase soil N$_2$O emissions by 60 MtCO$_2$e yr^{-1}, offsetting 28% of the soil carbon sequestration benefits. Although recent evidence suggests that modest amounts of carbon can be sequestered, about half of the global net mitigation potential of this option is in developing countries[56]. Carbon sequestration in grazing lands should perhaps be considered a co-benefit of improving productivity and ecosystems services[57], rather than a primary objective for managing grazing land ecosystems.”).

133 For e.g., *see* Reisinger A., Clark H., Cowie A. L., Emmet-Booth J., Gonzalez Fischer C., Herrero M., Howden M., & Leahy S. (2021) *How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals?*, Philos. Trans. R. Soc. A 379(2210): 20200452, 1–18, 8 (“Commercial availability of a vaccine is estimated to take 7–10 years after demonstration of a

prototype. Vaccine adoption could be facilitated by administering it in combination with other widely used animal vaccines. However, adoption rates will depend not only on costs but also on veterinary practices, as many animal vaccines are not adopted fully even where proven to be cost-effective [78].”).

134 Basu S., *et al*. (2022) *Estimating emissions of methane consistent with atmospheric measurements of methane and δ13C of methane*, Atmospheric Chemistry and Physics, 22(23): 15351-15377, 15352 (“As shown in Fig. 1, CH_4 levels have been rising rapidly since 2007 after a period of relatively slow growth in 1999–2006 (Dlugokencky et al., 2011; Saunois et al., 2020).”)

135 Bampidis V., *et al.* (2021) *Safety and efficacy of a feed additive consisting of 3-nitrooxypropanol (Bovaer® 10) for ruminants for milk production and reproduction (DSM Nutritional Products Ltd)*, EFSA J. 19(11): 1–35, 1 (“Consequently, the FEEDAP Panel concluded that Bovaer® 10 was safe for dairy cows at the maximum recommended level. However, as a margin of safety could not be established, the FEEDAP Panel could not conclude on the safety of the additive for other animal species/categories. The FEEDAP Panel considered that the consumer was exposed to 3-nitrooxypropionic acid (NOPA), which is one of the 3-NOP metabolites. NOPA was not genotoxic based on the studies provided. The FEEDAP Panel concluded that the use of Bovaer® 10 in animal nutrition under the conditions of use proposed was of no concern for consumer safety and for the environment. The FEEDAP Panel concluded that the active substance 3-NOP may be harmful if inhaled. It is irritant (but not corrosive) to skin, irritant to the eyes but it is not a skin sensitiser. As the genotoxicity of 3-NOP is not completely elucidated, the exposure through inhalation of the additive may represent an additional risk for the user.”).

136 Byrne J. (5 July 2023) *dsm-firmenich: Bovaer has saved 50,000 tons of CO2e to date*, Feed Navigator (“Authorities recently approved the sale of Bovaer in Paraguay, for use in dairy and beef cattle, making it the seventh country in Latin America to give the feed additives the green light, while Elanco Animal Health, dsm-firmenich’s strategic partner for developing, manufacturing, and commercializing Bovaer in the US, anticipates US approval and launch of the supplement in the first half of 2024.”). *See also* de Sousa A. (9 September 2021) *World’s Top Beef Supplier Approves Methane-Busting Cow Feed*, Bloomberg (“Latin America is the first region to grant approvals for the DSM product, which is also trying to get permission in the European Union, the U.S. and New Zealand. A trial on Brazilian beef showed Bovaer cut methane emissions from cows’ stomachs by as much as 55%, the company said. Bovaer has undergone trials in 13 countries, with more than 48 peer-reviewed studies published.”); *and* Bryce E. (30 September 2021) *Kowbucha, seaweed, vaccines: the race to reduce cows’ methane emissions*, The Guardian (“There are dozens more livestock methane interventions under development, according to a recent assessment co-authored by Ermias Kebreab. But only a handful – including Bovaer and Zelp – have reached the market. Even here, there’s still fine-tuning to be done. For instance Bovaer needs to be constantly in the rumen to work, meaning it may be less practical for free-ranging cattle whose feeding is less controlled (van Nieuwland said DSM is working to develop slow-release 3-NOP to help with this).”).

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