THE CLEAN COW

CUTTING THE CARBON FOOTPRINT OF US BEEF PRODUCTION

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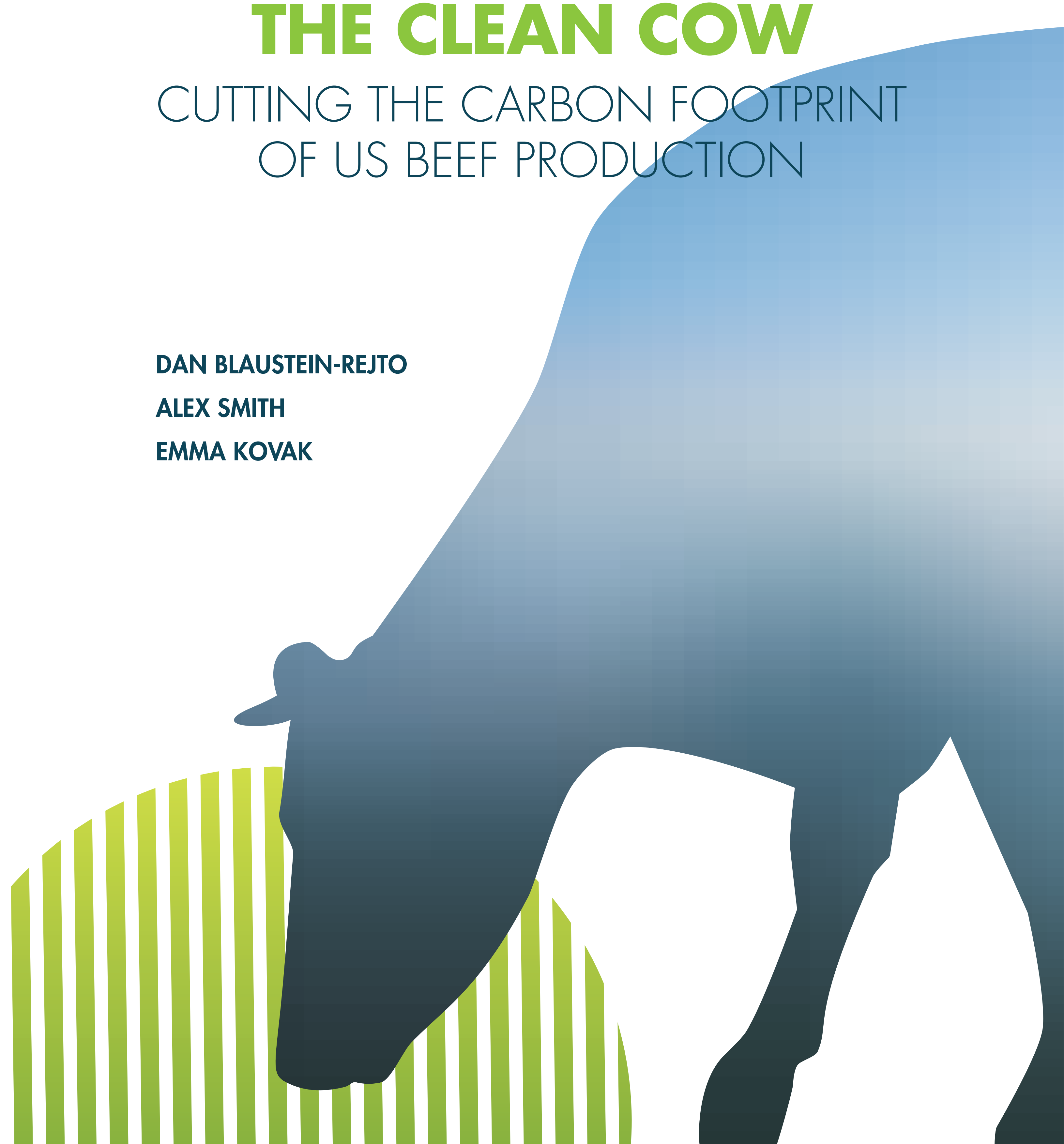


EXECUTIVE SUMMARY

In 2019, the United States produced approximately $111 billion worth of beef, exporting about 3 billion pounds and employing hundreds of thousands of workers, many in rural and semi-rural areas of the country. Beef cattle upcycle nutrients from grasses and other plants that are inedible to humans and provide a significant portion of US protein consumption. Although per-capita beef consumption has declined in the United States since the 1970s, beef remains a central part of the American diet and an important cultural touchstone.

Even so, raising cattle for beef is also responsible for about 3.2 percent of US greenhouse gas emissions. The largest share of US beef emissions comes from enteric fermentation, a digestive process in which microbes release methane, which is a potent greenhouse gas. Production of feed, such as corn, and manure management generate smaller yet significant levels of emissions.

This report assesses the potential to reduce beef's carbon footprint and identifies policies that could accelerate the decarbonization of the beef industry. Existing low-carbon technologies and practices include giving cattle in feedlots specialized feed additives that reduce methane emissions, composting manure, and changing how cattle are grazed. We find that full adoption of such practices by 2030, combined with business-as-usual reductions in emissions intensity, could reduce emissions from US beef production by 18 percent or 42 million metric tons of carbon dioxide equivalent per year.

We also identify a set of "breakthrough technologies," such as feed additives that can be given to grazing cattle, enhanced root crops that sequester more carbon than conventional plants, and breeding low-methane cattle. These advances are technologically plausible but still in the early stages of research. If these technologies were fully adopted alongside existing practices by 2030, we estimate that the carbon footprint of beef production could fall by about 48 percent.

Achieving even a fraction of this reduction will require overcoming steep technological, scientific, and financial barriers. It will necessitate not just private, but also public sector research and development. It will also be critical to expand programs that help producers adopt sustainable practices, develop new forms of support such as tax incentives, and reform regulations that stymie the development and commercialization of feed additives and genetically modified crops. Such changes would have large climate benefits and, in some cases, reduce land use and improve water and air pollution, making "clean," low-carbon beef possible.

To reach the goal of low-carbon beef, we recommend the following policies:

1. Increase federal funding for research on enhanced root crops, methane-reducing feed additives, breeding for feed efficiency and animal health, and use of anaerobic digesters in beef operations
2. Increase funding for federal farm conservation programs
3. Establish a federal program to support beef manure composting
4. Support pilot or experimental anaerobic digester projects
5. Establish a rebate program to incentivize the purchase of precision farming equipment
6. Update US Food and Drug Administration (FDA) and Department of Agriculture (USDA) regulations of methane-reducing feed additives and genetically modified crops and animals

CONTENTS

INTRODUCTION

Agricultural production is responsible for approximately 21%[1] of global greenhouse gas (GHG) emissions, and 11 percent[2] of US emissions. Of that, animal agriculture, and especially beef production, is the primary source (Figure 1). In the United States, beef production emits about 213.3 million metric tons (MMT) of carbon dioxide equivalent (CO_2e), more than chemical, cement, and metal production combined[3,4]

But beef is more than just environmental impacts. The US beef industry produced about $111 billion worth of product in 2019[5] — making up around 20 percent of global beef production[6] — and employs hundreds of thousands of workers, many in rural and semi-rural areas of the country.[7] Beef upcycles nutrients from grasses and feeds and provides a significant portion of the United States' protein consumption.[8,9] While per capita beef consumption has declined in the United States since the 1970s,[10] beef remains a central part of the American diet and an important cultural touchstone.

Enteric Fermentation and Feedcrop Production Account for the Majority of US Agricultural Emissions

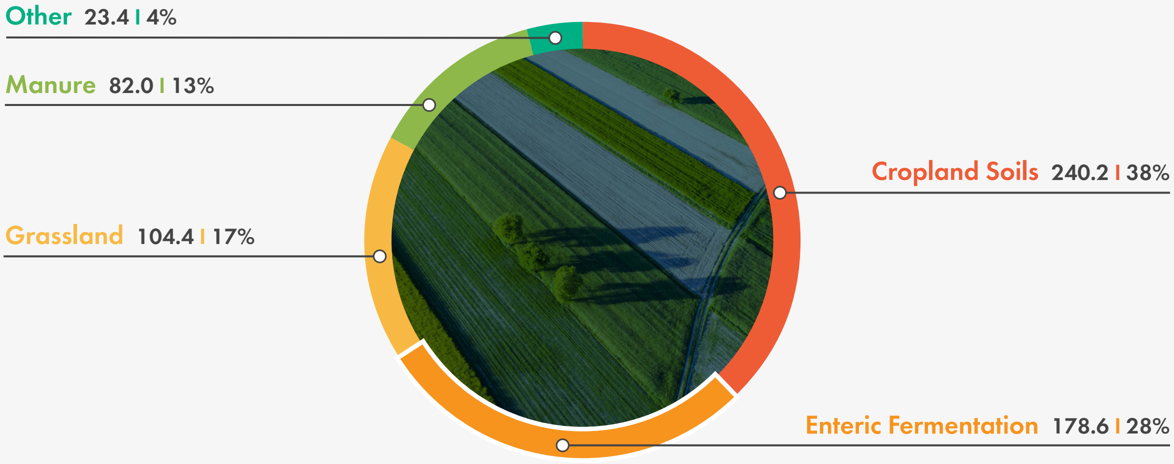


FIGURE 1: Greenhouse gas emissions from US agriculture in 2019 (million metric tons CO_2e).

Source: EPA (2021).[11]

With rising global demand for beef — driven largely by population growth and increasing wealth — enteric methane emissions (a by-product of cattle digestion) are projected to rise by more than 45 percent between 2020 and 2050.[12] Although efforts to shift diets toward low-carbon proteins could dampen the rise in beef demand, in the absence of extreme policy and cultural shifts, beef production is not likely to disappear. Thus, in order to advance global decarbonization, the United States must take a leading role in developing and adopting lower-carbon approaches to beef production.

New technologies and improved production practices have already reduced emissions from the US beef industry.[13] However, further environmental improvements are both possible and necessary (Figure 2).[14]

How To Cut Beef's Carbon Footprint

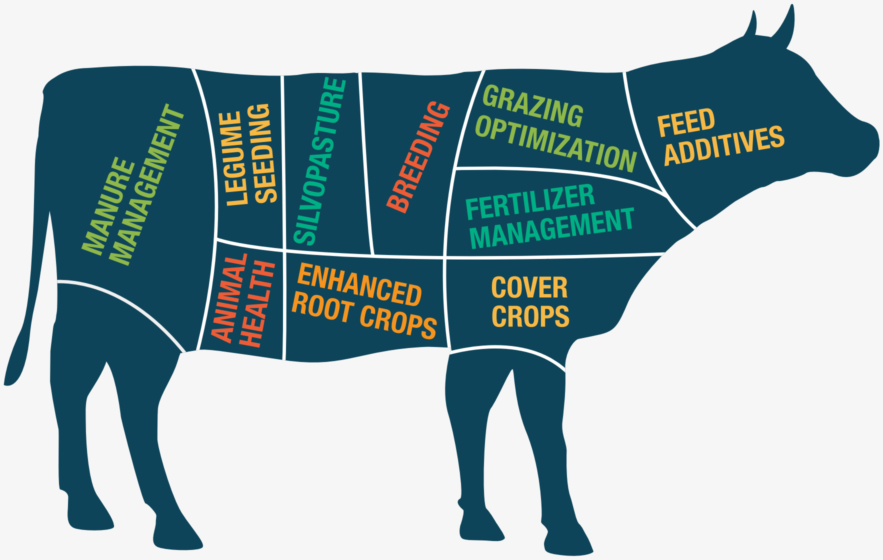


FIGURE 2: Options to reduce the carbon footprint of beef production.

In this report we outline how changes to grazing, animal feed, manure management, and other practices could make beef more climate friendly. Collectively, we estimate that business-as-usual reductions in emissions intensity and full adoption of existing low-carbon technologies and practices could reduce beef's carbon footprint in 2030 by nearly 18 percent, or 42 MMT CO_2e per year, more than many common proposals (Figure 3).

Technological breakthroughs, such as feed additives that reduce methane emissions from grazing cattle, could cut beef's carbon footprint even further. We estimate that fully adopting existing and breakthrough technologies, where possible, would reduce beef's carbon footprint up to 48 percent from current levels, making it nearly three times as carbon-intensive as pork and four and a half times as carbon-intensive as an Impossible Burger.[15,16,17] This level of mitigation would be equivalent to 18 percent of emissions from the entire US agricultural sector in 2019.[18]

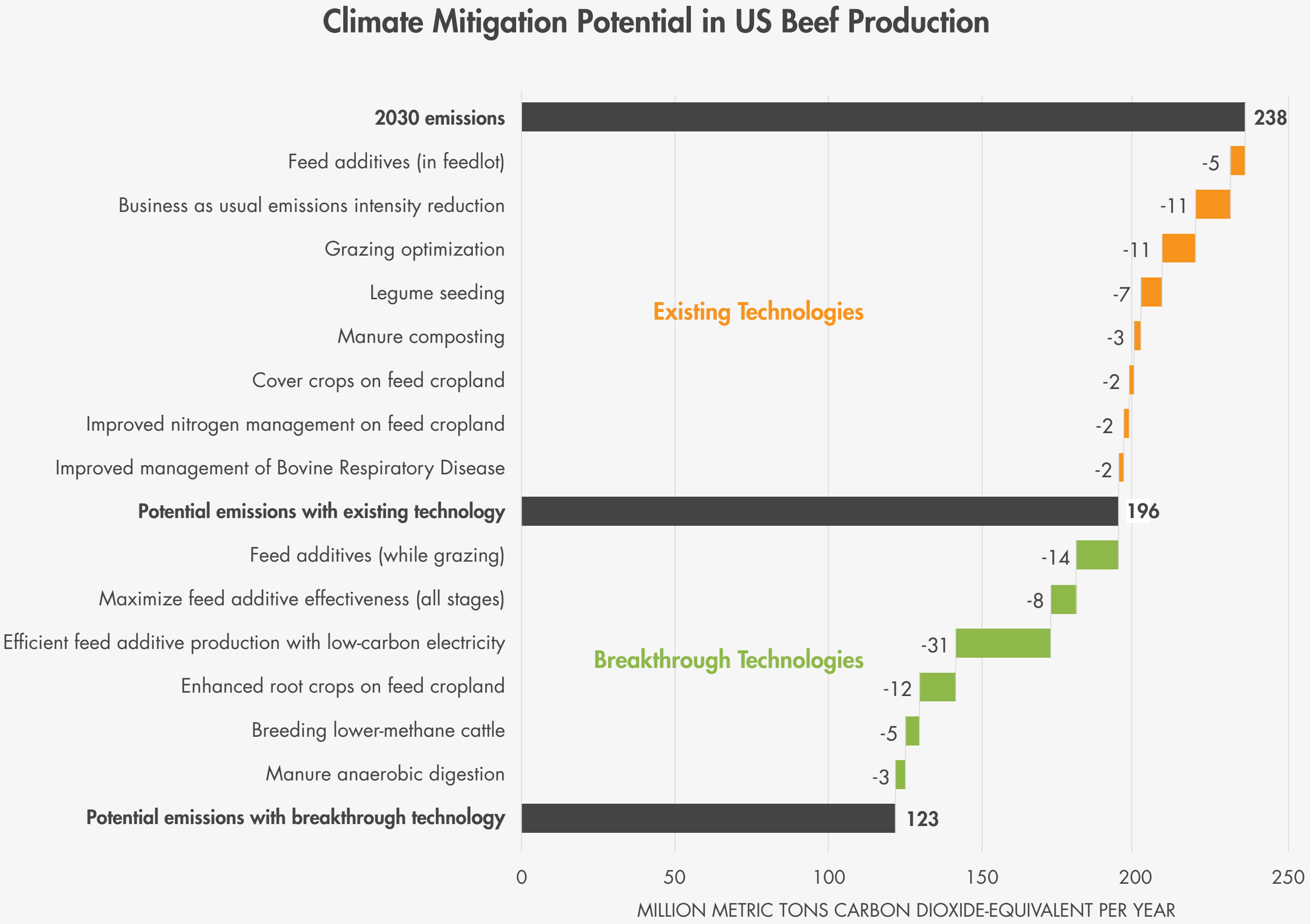


FIGURE 3: Potential of existing and breakthrough technologies and practices to mitigate GHG emissions of US beef production. Estimates shown are based on full adoption of practices, calculated using projected 2030 emissions from traditional beef breed cattle as the baseline.

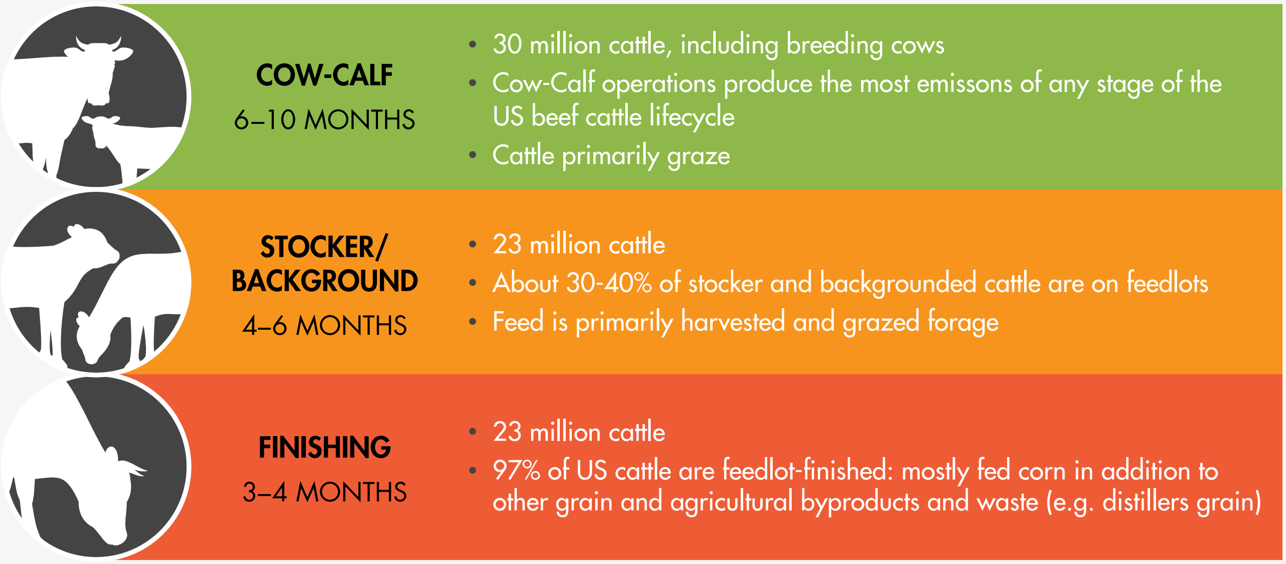
Achieving even a fraction of this reduction would require overcoming steep technological, scientific, and financial barriers that make widespread adoption infeasible today. It would necessitate not just private, but also public sector research and development (R&D), such as through the US Department of Agriculture (USDA)'s National Institute of Food and Agriculture. It would also be critical to expand USDA conservation programs that help producers adopt sustainable practices; to develop new forms of support such as tax incentives; and to reform regulations that stymie development and commercialization of feed additives and genetically modified crops. Such changes would have large climate benefits and, in some cases, reduce land use, improve water and air pollution, and even improve animal welfare, making "clean," low-carbon beef production possible.

In the next section, we describe the carbon footprint of US beef. We then assess the mitigation potential of technologies and management changes, such as those that receive substantial policy discussion (e.g., regenerative grazing), have nationally representative mitigation estimates published in peer-review journals or reports from leading nonprofit research groups, or whose estimates could reasonably be scaled up to the national level. We divide our assessment into four sections based on the mechanism for mitigation: (1) how cattle are fed, (2) pasture and rangeland management, (3) animal health, and (4) manure management. In the final section, we outline federal policy options to accelerate progress toward low-carbon beef production.

BEEF’S CARBON FOOTPRINT

Beef production generates approximately 3.2 percent of US GHG emissions[19] and 5.9 percent of global emissions.[20,21] The intensive, feedlot-based, large-scale production common in the US makes American beef less carbon- and land-intensive than beef in most other countries. However, it still has a large footprint compared with other protein sources. US beef has a carbon footprint of about 23.3 kg CO_2e/kg product — more than five times larger than that of pork and 10 times that of chicken.[22,23,24,25]

In the United States, beef calves are typically raised on pasture or rangeland for 6—10 months (Figure 4).[26] Some are transferred directly to feedlots, but most calves are placed first with a "stocker" or "background" operation, where they graze on grass or other forages, such as hay, for about 4—6 months.[27,28,29]Almost all beef cattle in the United States are then feedlot finished — that is, they live the last 3-10 months of their lives in enclosed feeding operations that utilize grain and other feed to increase weight gain.[30] On average, U.S. beef cattle spend 41% of their 18 month-long lives in feedlot systems when taking finishing and backgrounding operations in account.[31] Approximately one-fifth of beef is produced from dairy cows, such as bulls raised for beef.[32] However, in this report, we consider only the emissions and mitigation potential for beef produced from beef cattle.



COW-CALF
6–10 MONTHS

- 30 million cattle, including breeding cows
- Cow-Calf operations produce the most emissons of any stage of the US beef cattle lifecycle
- Cattle primarily graze

STOCKER/ BACKGROUND
4–6 MONTHS

- 23 million cattle
- About 30-40% of stocker and backgrounded cattle are on feedlots
- Feed is primarily harvested and grazed forage

FINISHING
3–4 MONTHS

- 23 million cattle
- 97% of US cattle are feedlot-finished: mostly fed corn in addition to other grain and agricultural byproducts and waste (e.g. distillers grain)

FIGURE 4: Lifecycle of US beef cattle.

Sources: Rotz et al. (2019), Capper (2012), Hayek & Garrett (2018), and Personal Communication with C. Alan Rotz.

Emissions Sources

The largest share of US beef emissions comes from enteric fermentation (Figure 5).[33] Enteric fermentation is a digestive process in which microbes decompose and ferment food, releasing the potent greenhouse gas methane (CH_4). Methane has about 28 times the global warming potential of carbon dioxide over 100 years.[34,35] Most of the methane from beef production (about 77 percent) arises when cattle are grazing on pasture and rangeland before being transferred to feedlots.[36] In fact, contrary to popular belief, the majority of all life-cycle GHG emissions from beef production come from grazing cattle, largely from cows used for breeding, rather than from cattle in feedlots.[37]

Pasture, range, and cropland also account for a large share of beef's carbon footprint.[38] Cattle deposition of urine and manure on pasture and the application of fertilizer to crops for animal feed release nitrous oxide,[39] a gas with about 265—298 times the global warming potential of carbon dioxide over a 100-year timescale.[40]

Manure, which releases both methane and nitrous oxide, accounts for a smaller, yet significant, portion. Upstream sources such as electricity, fertilizer, and fuel production each account for a small portion, as do anthropogenic CO_2 sources such as on-farm fuel combustion.[41]

Enteric Methane Is the Largest Source of Beef Emissions

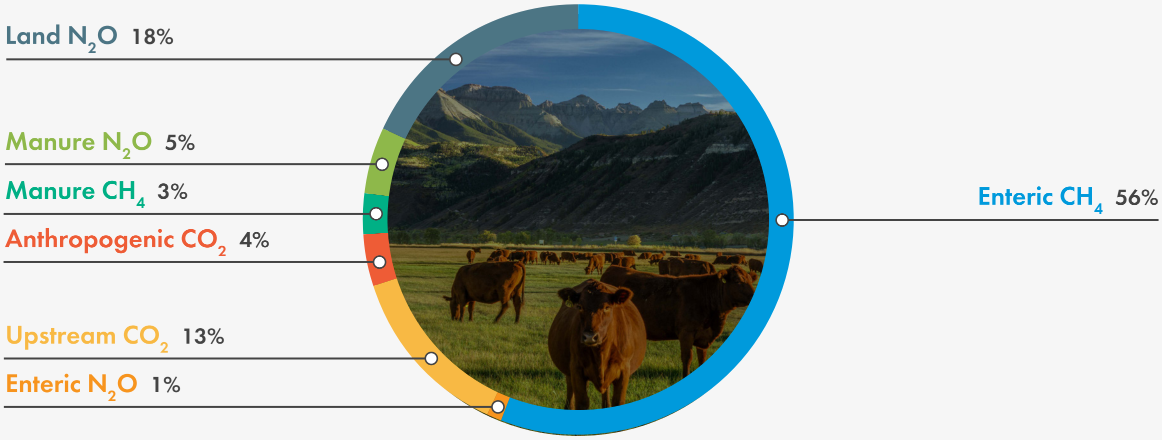


FIGURE 5: Carbon dioxide equivalent (100-year global warming potential) from US beef production by source.

Source: Rotz et al. (2019), Figure 3a.

Carbon Footprint in Context

Several researchers have recently suggested that beef's carbon footprint may be larger than most studies and the US Environmental Protection Agency (EPA) estimate. Studies that measure atmospheric GHG levels above animal operations and model what portion came from animal operations versus other sources (e.g., gas fields) estimate that all farmed animals in the US emit 39—81 percent more methane than EPA estimates.[42] If methane emissions for beef cattle have been underestimated by the same amount, the carbon intensity of US beef production could be as high as 28.4—33.9 kgCO$_2$e/kg.[43] However, estimates based on atmospheric monitoring, as with bottom-up estimates such as the EPA's, contain large uncertainties. Further, little work has been done either to incorporate them into official emissions reporting or to reconcile estimates conducted using different methods.[44]

Nevertheless, the carbon intensity of US beef is lower than that of any other major beef-producing country, in large part owing to its intensive, large-scale, grain-finished production (Figure 6).[45,46] While only 7—13 percent of beef is produced with feedlots globally, almost all US beef is.[47] Only 3 percent of US beef cattle are grass finished, that is, fed exclusively on grass and other forage throughout their life.[48] Grain- or feedlot-finished animals are more efficient at turning feed into meat, gain weight faster, and reach a higher overall carcass weight. They thus produce less enteric methane per kilogram of meat produced and have a lower net carbon footprint.[49]

US Beef Is Less Carbon-Intensive Than Beef from Other Top Producers

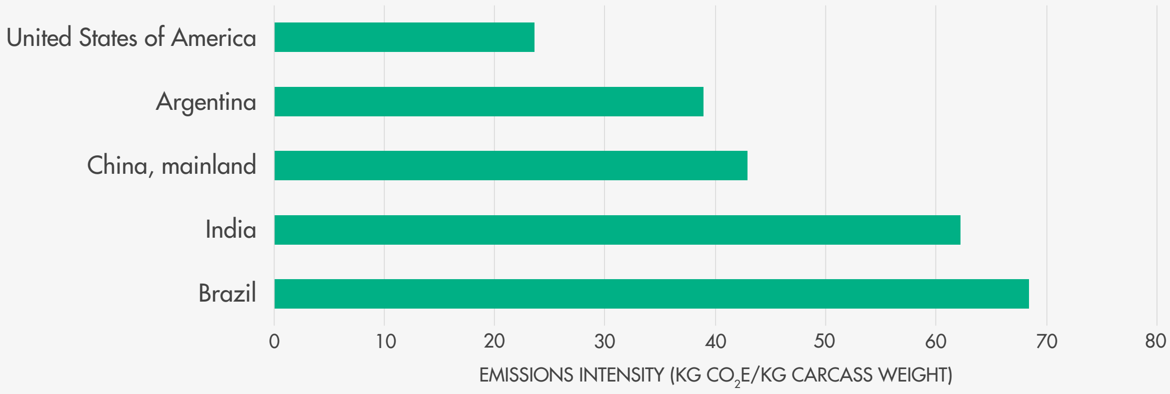


FIGURE 6: Emissions intensity of beef production in the top five beef-producing nations.

Source: Kim et al. (2020)[50].

US feedlot beef cattle also use less agricultural land than grass-finished beef cattle or those from other countries. Although feeding grain to cattle requires cropland to grow the feed, it reduces the amount of land needed for grass and forage production. In fact, shifting current levels of beef production from grain-fed exclusively to grass-fed production would require additional land and cattle, encroach on native ecosystems, and potentially compete with the human food supply.[51]

In addition, beef production requires substantial water use for feed production[52] and generates air and water pollution.[53] Manure and fertilizer release excess nitrogen in the form of nitrate (NO_3) in waterways, causing eutrophication, which can lead to dead zones in fresh and marine water bodies, suffocating fish and causing economic harm to fisheries. These agricultural fertilizers also emit ammonia (NH_3), which contributes to the development of particulate matter, a type of harmful air pollution.

HOW CATTLE ARE FED

Feed has a large impact on the carbon footprint of beef production. What and how cattle are fed influence methane emissions through enteric fermentation, the productivity (and thus lifespan) of cattle, and the level of land use and emissions involved in producing feed.

Despite the well-known problems with concentrated animal feed operations (CAFOs), such as animal welfare and water pollution from manure, by increasing weight gain and reducing the amount of time cattle spend grazing and emitting methane, feedlot finishing results in lower net land use and GHG emissions than finishing cattle just on pasture.[54]

But feedlot finishing requires growing extensive crops for feed. Corn and soy production for beef cattle feed uses about 15 million acres of land.[55,56] The fertilizer and fuel used to grow these and other feed crops, such as alfalfa, generate as much as 18 percent of beef's total carbon footprint.[57,58] Still, reducing the climatic impacts of beef would mean improving how cows are fed.

We highlight four pathways for reducing GHG emissions through feed: improving the production of feed crops, changing from conventional feed and developing novel feeds; utilizing feed additives that reduce emissions; and breeding cattle for improved feed efficiency. Although some of these mitigation practices, such as cover cropping, are feasible today, others require future breakthroughs such as the development of crops with enhanced root systems that could sequester more carbon in the soil.

Cutting Emissions from Conventional Feed Crop Production

As shown above, feed crop production has a large environmental footprint. Even so, improving farming practices and adopting new technologies could reduce the emissions caused by feed production.

Although beef cattle in the United States consume mostly grass and other forage, corn and soy account for about 11 percent of their diet and have an outsized environmental impact. In fact, up to 15 percent of feed consumed in beef production derives from sources that could also be used for human consumption.[59] Feed crop production involves substantial irrigation and pesticide application, and contributes to air pollution, water pollution, soil erosion, and greenhouse gas emissions.[60] Corn production alone accounts for about 3 percent of beef's total carbon footprint, stemming largely from nitrous oxide (N_2O) emissions from fertilizer use.[61,62]

One effective approach for reducing N_2O emissions is to apply fertilizer when and where plants need it and to find ways for plants to need less nitrogen. Precision farming tools, such as nitrogen sensors, enable farmers to better match fertilizer application to crop needs and thereby reduce excess nitrogen levels. Nitrification and urease inhibitors can also help. These compounds can be mixed with fertilizer to reduce the amount of nitrogen converted to nitrous oxide and thereby keep more of the nitrogen in the soil to feed the crops. We estimate that full adoption of precision farming equipment and inhibitors on corn and soy farms could reduce feed production emissions in 2030 by about 2 MMT CO_2e.[63]

In addition, widespread planting of cover crops — to cover the soil outside the regular growing season — could sequester nearly another 2 MMT CO_2e.[64] No-till agriculture, though it reduces erosion and has other environmental benefits, is unlikely to substantially sequester carbon, according to recent evidence.[65] Grazing animals on cropland or rotating cropland and pasture can also increase soil carbon sequestration,[66,67] but this practice remains poorly studied with insufficient research to estimate national mitigation potential.[68]

Adoption of each practice faces unique barriers. For instance, precision farming equipment and cover cropping may save farmers money in the long run but have high up-front costs. Other practices, like applying nitrification inhibitors, cost farmers additional money without generating substantial revenue. To address these barriers, technical and financial assistance should be tailored to help different types of farmers adopt a variety of practices and technologies.

Technological breakthroughs could also provide greater mitigation. Ensuring all corn and soy feed comes from crop varieties with "enhanced root systems" that sequester more carbon than current varieties could sequester 12 MMT CO_2 per year.[69] Scientists at the Salk Institute, Penn State, and elsewhere are working to research, develop, and test such crops, though they estimate it will take years if not decades. Further R&D could enable the production of fertilizer using clean energy sources instead of natural gas.

Methane-Reducing Animal Feed Additives

Feeding beef cattle substances to reduce their enteric methane emissions is a relatively novel emissions mitigation strategy. These feed additives have been touted as potential breakthrough technologies to improve the environmental impact of agriculture but face barriers related to cost and regulatory approval.

The products can be split into two main categories: methane inhibitors and rumen modifiers. Rumen (methane) inhibitors act on and disrupt the process of methane production in the cattle rumen, whereas rumen modifiers change the makeup of the rumen in ways that limit methane production.[70]

The effectiveness of feed additives depends on the kind of production system in use (Figure 7). Cattle that are fed high-fiber forage diets — which includes cattle in the cow—calf and stocker phases of production — have greater rates of enteric fermentation.[71] These high-fiber diets also limit the efficacy of some products. Recent research has indicated that methane inhibitors are about two-thirds as effective in reducing emissions from cattle while grazing than while in a feedlot,[72] though some rumen modifiers may be more effective with such high-fiber diets.[73,74] Regardless, more research is necessary to study the efficacy of additives in grazing systems as well as how best to provide them to grazing cattle, such as by incorporating them into mineral blocks.

Feed Additives Can Substantially Cut Methane Production in Feedlots

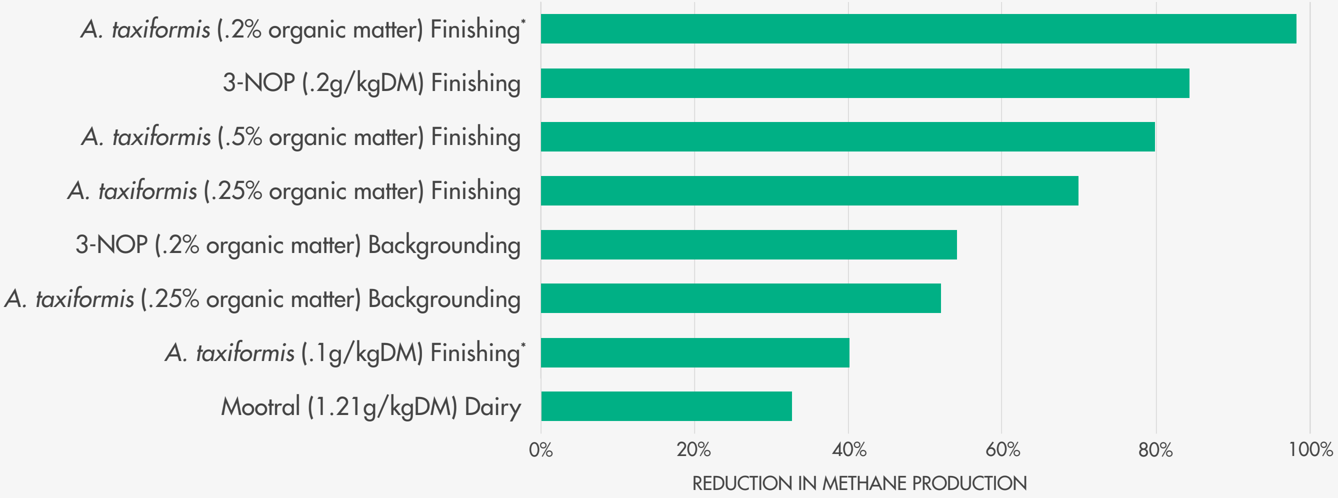


FIGURE 7: Efficacy of feed additives for reducing methane emissions from beef cattle in backgrounding and finishing feedlot environments. Reductions are measured as percentage change in CH_4 emissions per day.

*Reductions measured as percentage change in CH_4 per kilogram of dry matter intake. Additives are included at different levels of grams per kilogram dry matter (DM) and percent organic matter.

Sources: Roque et al. (2021), Vrancken et al. (2019), Kinley et al. (2020), and Vyas et al. (2016, 2018).[75]

We estimate that feeding *Asparagopsis taxiformis*, produced with carbon-intensive electricity, to all beef cattle grazing and in feedlots could reduce beef's total carbon footprint by about 7 and 2 percent, respectively. Feeding all beef cattle higher levels of *A. taxiformis*—if it is as effective in all operations as it has been in studies—could reduce beef's carbon footprint as much as 14 percent. Using *A. taxiformis* produced with low-carbon electricity and with twice the regular bromoform content could reduce emissions as much as 33 percent.[76]

3-NOP

3-nitrooxypropanol, or 3-NOP, is one of the most studied methane inhibitors. 3-NOP works by neutralizing an enzyme in the cattle rumen that is key to the process of methanogenesis. Whereas the application and use of 3-NOP depend in part on the production system, it has been relatively effective across the board without animal health or productivity tradeoffs.[77,78] Currently, DSM, a Dutch-based multinational company, produces 3-NOP in Europe under the brand name Bovaer. Still, 3-NOP has yet to gain regulatory approval in the United States or European Union for use as a feed additive.[79]

Asparagopsis taxiformis

Asparagopsis taxiformis—a type of red seaweed—is another well-studied methane inhibitor. *A. taxiformis* contains bromoform and other chemical compounds that interfere in methanogenesis and reduce cattle methane production. Still, questions remain as to the long-term effectiveness of *A. taxiformis*—there is concern that cattle rumens could adapt to the halogenic compounds and return to previous methanogenesis levels, especially if cattle are fed *A. taxiformis* for their entire lives.[80] Optimistically, one recent study found that *A. taxiformis* can remain effective for at least 147 days, or roughly the length of feedlot finishing.[81]

The widespread use of *A. taxiformis* is limited by a lack of seaweed production in the United States as well as the need for regulatory approval as a feed additive.[82] While seaweed cultivation is a large industry in parts of East Asia, *A. taxiformis* is not currently cultivated at scale.[83] Blue Ocean Barns, a US-based company that aims to produce *A. taxiformis* for use as a feed additive, claims they will be able to produce enough of the seaweed to be used for all beef and dairy cattle in the United States by 2030.[84] Additionally, emissions from the production and transportation of *A. taxiformis* could offset a portion of the emissions reduction that results from feeding it to cattle. Life-cycle assessments of *A. taxiformis* are needed to fully understand its total mitigation potential.

Mootral

Mootral is a blend of essential oils and other ingredients—including garlic and citrus extracts—that works as a rumen modifier to reduce the methane production of cattle. Essential oils work to reduce methanogenesis by changing the chemical makeup of the rumen and limiting the growth of methanogens—bacteria that break down materials in the cattle rumen and release methane.[85] Research on essential oils has found potential methane reductions from extracts of lemongrass, citrus, garlic, oregano, and other products, but no single essential-oil compound has shown high anti-methanogenic properties across multiple studies. Mootral, on the other hand, is relatively well studied, effective, and being commercialized.

Breeding Cattle for Feed Efficiency

Cattle breeding can play a significant role in reducing the greenhouse gas emissions related to enteric fermentation. From 1961 to 2018, enteric methane emissions per unit of beef decreased in the United States by 36 percent, due in large part to improved breeding as well as management (Figure 8).[86,87] Breeding cattle that grow bigger and faster has reduced the number of cattle and the resulting methane emissions needed to produce each pound of beef. Despite the success of past breeding in increasing cattle size and growth rate, there remains a wide range of efficiencies with which individual cattle convert feed to meat; therefore, potential remains for furtherfeed efficiency gains through breeding.[88]

Breeding for feed efficiency is necessary because measuring methane emissions directly is time-consuming and expensive. As a result, a large body of research has focused on identifying proxy traits for methane emissions, many of which are metrics of feed efficiency, which are easier to measure and therefore improve through breeding. However, experts disagree, and more research is needed to identify which feed efficiency metrics are the best proxies for methane emissions.[89]

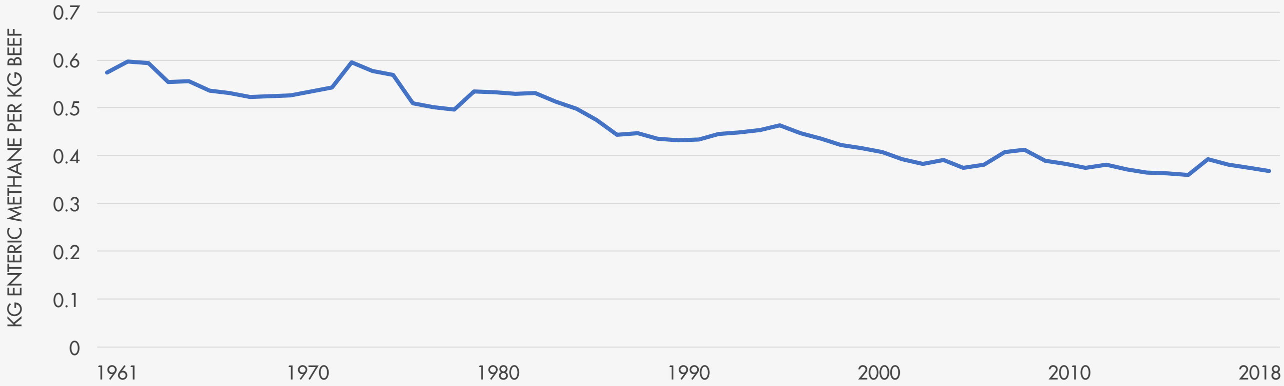

Enteric Methane Emissions per Unit of Beef in the United States Have Decreased 36 Percent Since 1961

FIGURE 8: Enteric methane emissions from non-dairy cattle in the United States. Does not include methane emissions from manure management.

Source: FAOSTAT (2021), http://www.fao.org/faostat/en/#data/QCL and http://www.fao.org/faostat/en/#data/GE.

The use of a technology called *genomic breeding* also has the potential to improve cattle breeding by speeding up the rate of genetic change in desired traits and could be used to improve breeding for feed efficiency in order to reduce methane emissions. Genomic breeding involves "reading" the entire genetic code from an individual animal — which comprises thousands of genes — and pairing this information with measurements of traits to allow researchers to identify genes that impact those traits. Once there is a clear link established, breeders can make decisions using genetic information as a proxy for desired traits without having to measure them. This is particularly useful for traits that are time-consuming or expensive to measure, such as the level of enteric methane emissions.

Genomic selection can reduce the time between generations from five or more years to less than two years and increase the rate of genetic change in desired traits by an estimated 12—100 percent, based on research in dairy cattle.[90,91] Genomic breeding technology is already widely used in the US dairy industry, with over half of the artificial inseminations stemming from genomically tested bulls.[92] In comparison, adoption of both artificial insemination and genomic selection in beef cattle breeding is lagging.

We estimate that if 50 percent of US beef cattle breeders selected for feed efficiency, US beef emissions would fall by about 1.6 percent by 2030 and up to 4.5 percent as breeding efforts advanced over the course of years or decades. If such a program also encouraged the use of genomic breeding for increasing feed efficiency, we estimate a larger decrease of roughly 2.4 percent by 2030.[93] Achieving such widespread adoption would likely require federal support; for example, Ireland's Irish Cattle Breeding Federation program supports genomic breeding.[94] International collaboration and data sharing could also advance the use of genomic sequencing in US beef cattle breeding.[95]

RANGELAND AND PASTURE MANAGEMENT

Beef production involves vast amounts of land for grazing. Nearly 800 million acres are used for livestock grazing in the United States, equivalent to 35 percent of the land area of the continental US.[96] Cattle are grazed primarily on pasture and rangeland.[97,98] Rangelands are uncultivated grasslands, shrublands, and other lands on which the native vegetation is suitable for grazing. They are managed primarily by grazing. Pasture, on the other hand, is land that is more intensively managed, for instance, through seeding, irrigation, and fertilization, to grow grasses and other forage plants for grazing animals.[99]

Widespread changes in how this land is grazed, planted, and otherwise managed could technically sequester enough carbon to offset up to 42 percent of beef's carbon footprint per year by 2030, but any decline in cattle productivity would negate much of the benefit (Figure 9).[100] These changes are also costly, difficult, and impractical on most grass and rangeland. Additional research may be able to reduce costs, such as that of establishing trees on pasture. But widespread change will also require new incentives and support for ranchers and land managers, such as financial and technical assistance.

Pasture Management Has Large Sequestration Potential, but Yield Reductions Limit Net Climate Benefits

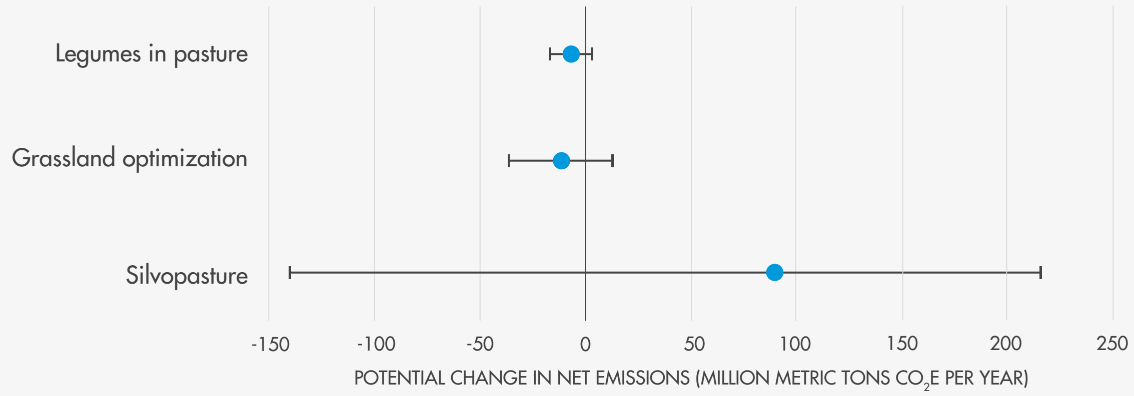


FIGURE 9: Climate mitigation potential of pasture and rangeland management changes.

Circles indicate primary estimates. Black lines indicate the range for silvopasture,[101] and the 95 percent confidence interval for grassland optimization and legumes in pasture.[102] Positive (negative) values indicate increases (decreases) in net emissions. Silvopasture estimate includes change in carbon benefits due to the reduction in beef yield typically associated with silvopasture adoption in temperate environments.[103]

Regenerative Grazing

A variety of grazing practices and regimes, often referred to as "regenerative," can potentially increase soil carbon (C). For example, adaptive multi-paddock (AMP) grazing involves frequent rotation of animals at high densities between different enclosures of land called "paddocks." By allowing plants to recover after being grazed, protecting soils, and promoting plant growth, AMP can reduce soil erosion, improve animal productivity, and increase soil C sequestration.[104] Although rarely discussed, AMP and similar practices can be implemented during the cow—calf phase for cattle that are later sent to a feedlot, in addition to those that are grass-fed their entire lives.

Although individual studies have found high rates of soil C sequestration, we believe that the national mitigation potential of regenerative grazing is too uncertain to estimate at this time. Estimates of soil C sequestration rates from AMP and related grazing approaches vary widely. Some studies have observed rates as high as 1.45 metric tons/hectare per year,[105] while others have found no difference in soil carbon stocks between prairie with AMP and light continuous grazing.[106] Further complications in estimating average sequestration rates or national mitigation potential are that sequestration rates are highly context-dependent and that sequestered carbon can be lost due to management or climatic changes, fires, or conversion of grassland to cropland.[107] Finally, shifting any amount of land from feedlot to grass-finished production, whether regenerative or not, typically reduces beef production per acre.[108] This is not inherently problematic, given that much rangeland is not suitable for other purposes such as crop production.[109] However, to meet constant or growing global beef demand with less production in the United States would require other countries to increase production. New beef production, especially in the tropics, often involves deforestation and other types of land use change. Therefore, shifting from feedlot production to grass-finished production could have a high carbon cost.[110] More research is needed to determine how this carbon cost compares with the climate benefits from regenerative grazing.

However, it is possible to roughly estimate the sequestration potential of grazing in ways that increase the production of forages, like grasses, that cattle graze on. For example, reducing the number of cattle grazing per acre (the stocking rate) in areas that are overgrazed and increasing it in areas that are undergrazed could increase both forage growth and livestock production (Figure 10). If carried out on roughly one-fifth of grazing land, this adjustment of stocking rates could sequester up to 11 MMT CO_2e/year.[111]

Changing Cattle Stocking Rates Could Sequester Carbon in Pasture and Rangeland

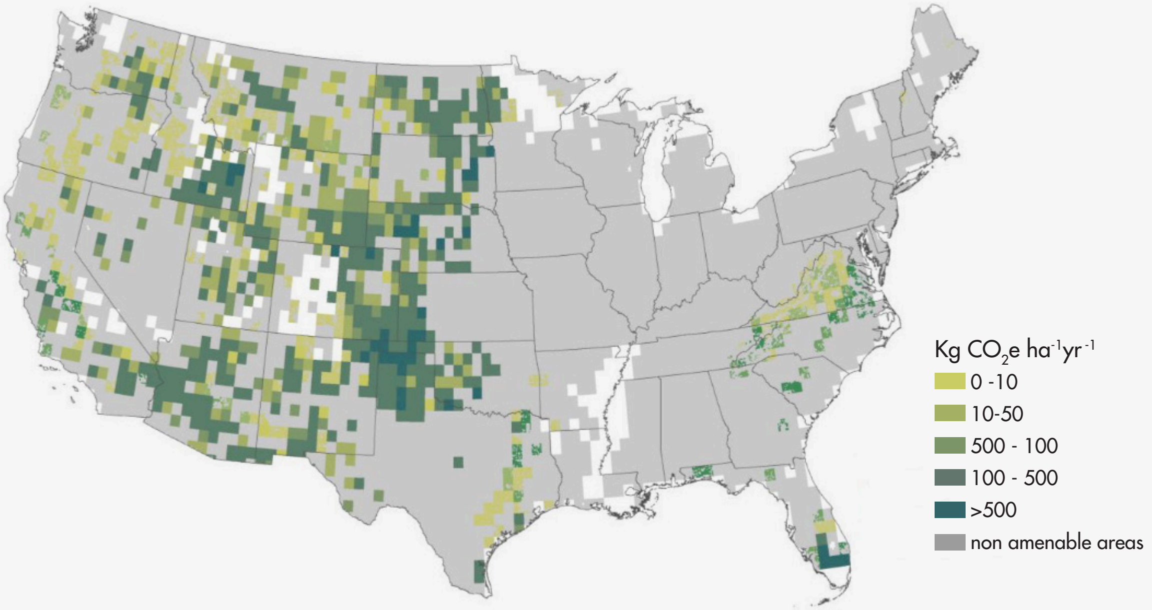


FIGURE 10: Grazing optimization mitigation potential. Areas in white do not contain grassland with more than one cattle per square kilometer. Gray areas indicate that grazing optimization would not result in additional carbon sequestration.

Source: Fargione et al. (2018), Supplementary Materials, Figure S17.[112]

Planting Legumes on Pasture

Planting legumes (plants such as clover and alfalfa that add nitrogen to the soil) in pasturelands can marginally increase carbon sequestration. Although seeding some rangeland with legumes is possible, we only consider seeding on pasture because legume seeding often requires active management such as weed control, requires specific environmental conditions such as sufficient rainfall levels not found on much rangeland,[113] and risks replacing native plants on rangeland.[114] Although planting legumes on pasture can result in significant carbon sequestration per acre, it also adds nitrogen to the soil and thus can generate additional emissions of nitrous oxide — a potent greenhouse gas.

Accounting for both sequestration and nitrous oxide emissions, planting legumes would result in net sequestration on only 13 percent of planted pasture in the United States — nearly 14 million acres.[115] The mitigation potential of planting legumes is thus relatively low: about 7 MMT CO_2e/year.[116] In addition, the costs associated with seeding, labor, weed control, and machinery generally prohibit ranchers from planting legumes without external financial incentives.[117]

Silvopasture

The integration of trees into pasture, known as silvopasture, can also sequester a large amount of carbon in trees and soil.[118] Planting trees on the 69 million acres of pastureland that have historically supported forest cover[119] could sequester 81 MMT CO_2e.[120,121] Although estimates of carbon sequestration vary widely — from at least 0.55 to 1.90 metric tons C/hectare per year[122] — even the most conservative estimates indicate that silvopasture adoption could sequester more carbon than other grazing practices.

However, widespread silvopasture adoption may have little to no net climate benefit. Planting trees on pasture — though it provides shade and can reduce heat stress for cattle — typically reduces forage and cattle production per acre in the US and other temperate environments.[123] We estimate that the reduction in cattle productivity from conversion to silvopasture would, by shifting production to other regions, actually increase net emissions.[124] In addition, harvesting the timber, which is often necessary to make silvopasture financially feasible, could reduce carbon storage including in the soil as tree root systems die and decompose.[125] Yet harvesting timber from silvopasture could also reduce timber harvest and deforestation in other countries or places. Lacking an estimate of the potential carbon benefits of this dynamic, we exclude silvopasture from our estimates of total climate mitigation potential.

Financial, logistical, and behavioral barriers also limit adoption. Scaling up silvopasture without external subsidies or incentives is expensive for producers, costing upwards of $40 to $186 per acre, even when accounting for potential income from timber.[126] In addition, planting and maintaining trees requires labor, specialized skills, and landowner interest in changing management practices.

ANIMAL HEALTH

Every cattle death due to illness results in unnecessary resource use and environmental impacts. Even for animals that recover from illness, being sick often reduces their growth rate, and thus increases the GHG emissions per unit of the final product. Improvements in veterinary and animal health practices that reduce illness and death could mitigate the overall GHG emissions of beef production.

Bovine respiratory disease (BRD) is the largest disease-related cause of herd loss in the United States and is responsible for 45—55 percent of all cattle deaths in the feedlot.[125] Even when BRD is not fatal, the disease decreases the average daily weight gain of cattle,[126] increases feed consumption,[127] and ultimately increases enteric methane emissions. We estimate that if the number of cattle that die due to BRD decreased by 50 percent, emissions from US beef production would fall 1 percent.[128]

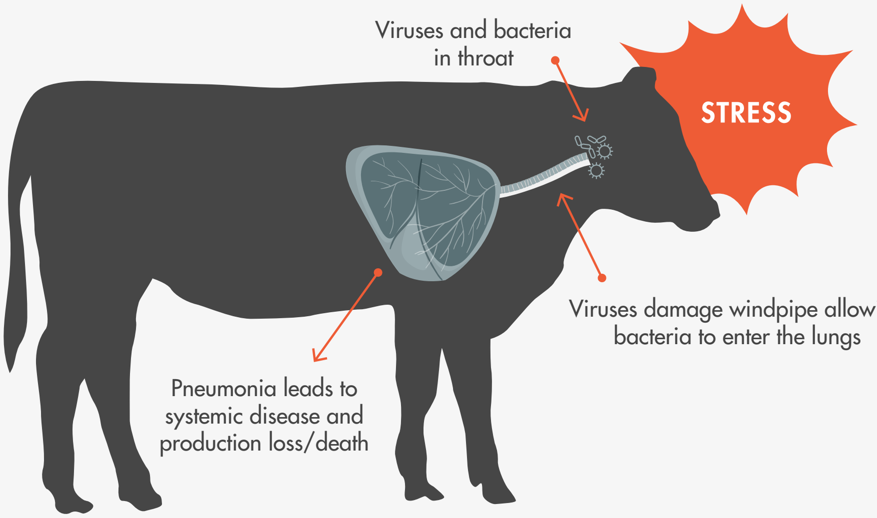


FIGURE 11: Effects of bovine respiratory disease. Viruses and bacteria that can cause BRD live in the animal's throat. Stress can trigger BRD, which progresses via viruses damaging the windpipe, allowing bacteria to enter the lungs and cause pneumonia. This, in turn, leads to systemic disease and causes production loss and sometimes death.

Source: New South Wales Government Local Land Services, "Bovine Respiratory Disease" (April 2020), https://www.lls.nsw.gov.au/regions/central-west/articles-and-publications/animal-health-and-disease/bovine-respiratory-disease.

Vaccination for Bovine Respiratory Disease

Current BRD vaccination practices are inefficient and poorly suited to preventing the disease. Although evidence shows that BRD vaccines are efficacious when delivered in the cow—calf phase, only 39 percent of cow—calf operations vaccinate their cattle. Instead, most BRD vaccinations occur either immediately upon arrival at stocker and background operations, or immediately when cattle arrive at feedlot facilities for finishing.[129,130,131] These cattle are often chronically stressed and have suppressed immune systems that make the vaccine less efficacious. Instead of relying on mass vaccination of cattle at feedlots — 90 percent of US feedlots vaccinate cattle upon arrival[132] — the industry should further research and consider vaccinating the majority of cattle at cow—calf operations, where cattle are less stressed and the vaccine can be more efficacious.[133]

Additional research into vaccine administration could also help to stem the rise of antimicrobial resistance. Many microbes that commonly cause BRD have developed a high level of antimicrobial resistance.[134] Mass treatment and prophylaxis for BRD represent a large portion of antimicrobial use in cattle.[135,136] Improving vaccination is an important part of disease prevention and can subsequently prevent growing antimicrobial resistance.[137]

Breeding for Disease Resistance

Breeding for disease resistance is another potential approach to reduce the incidence of BRD since some cattle are less susceptible than others to the disease.[138] This approach could benefit from genomic sequencing that could identify the genetic markers for disease resistance without necessarily tracking disease susceptibility over the lifetime of many individuals.

Genetic engineering has also proven to be a useful tool to increase disease resistance in livestock, notably with mastitis-resistant cows and porcine reproductive and respiratory syndrome (PRRS)—resistant pigs.[139,140] Genetic engineering could help develop cattle that are resistant to BRD. However, the process of creating a new genetically engineered animal can be lengthy, likely taking over a decade. Additionally, for genetic engineering to be a useful tool in cattle breeding, US regulations would have to dramatically change to lower the astronomical barriers to bringing such an animal to market.[141]

MANURE MANAGEMENT

Manure from beef cattle operations produces approximately 7.4 percent of emissions from beef production, or roughly 16 MMT CO_2e/year.[142] Like other emission-intensive aspects of beef production, most manure-related emissions originate from cow—calf and stocker operations, where cattle defecate on pastures, releasing both methane and nitrous oxide into the atmosphere. About 70 percent of manure-related emissions, or roughly 11 MMT CO_2e/year, stem from feedlot production systems used at finishing or backgrounding operations, which is where emissions from manure can most easily be reduced.[143] Even so, reducing GHG emissions related to beef cattle manure from feedlots will not be easy, or cheap.

Currently, cattle manure from feedlots usually follows one of two paths: composting, to be sold as soil amendments, or dry-lot storage, followed by direct application on nearby crop fields. Approximately 20 percent of manure from feedlots is composted and 78 percent stored as is until field application.[144] The remaining 2 percent is managed in lagoons and through other methods.

If barriers to adoption were overcome, composting (or anaerobically digesting beef cattle manure that is not already composted) could moderately reduce emissions related to beef manure on feedlots. Nevertheless, given feedlot manure's relatively small emissions share, even major shifts in manure management could only marginally reduce beef's total carbon footprint emissions.[145]

Composting

Composting increases the value of manure as a soil amendment because it makes the nutrients more bioavailable to plants and can be used for more-targeted applications in crop production than simply applying manure to a field.

Composting can mitigate greenhouse gas emissions from manure storage,[146] but its effects depend on weather, climate, and the specific composting practice used, among other factors. In some circumstances, composting can even increase net GHG emissions. However, windrow manure composting, in which manure is piled into long rows along with other organic material and is aerated through manual or automatic turning, emits up to 30 percent less CO_2e than typical dry-lot storage, depending on the frequency of aeration.[147,148] Incorporating other materials into the composting process, such as biochar and dried grass, could further reduce emissions.[149] Beyond reducing emissions related to manure storage, composting manure could have significant soil carbon sequestration benefits when applied to either cropland or rangeland.[150]

Nonetheless, adopting composting practices is difficult. Costs remain high — especially for intensively aerated windrow composting, the practice most effective at reducing emissions.[151] Composting involves up-front investments as well as ongoing operation and maintenance costs. At the same time, successful adoption would require more frequent manure removal from cattle lots to realistically reduce GHG emissions.

Anaerobic Digestors

Anaerobic digestion is another option for reducing manure emissions (Figure 12). Anaerobic digesters break down manure in enclosed environments in the absence of oxygen. They produce methane-rich biogas that can be sold or burned on site to create energy. The remaining nutrient-rich material following the process of digestion, called digestate, may also be used as a soil amendment. Anaerobic digesters reduce emissions from cattle manure by collecting methane and nitrous oxide. Even though biogas from digesters is combusted, the total emissions are less than those from business-as-usual management.[152,153]

Digesters are used predominantly in dairy operations where frequent manure collection supplies digesters with constant manure.[154] Beef operations, on the other hand, often do not collect manure frequently, meaning that inorganic materials, e.g., bedding, rocks, dirt, or other debris, collect alongside the cattle manure, preventing effective anaerobic digestion. Shifting from current manure management strategies to anaerobic digestion would require altering broader manure collection practices.

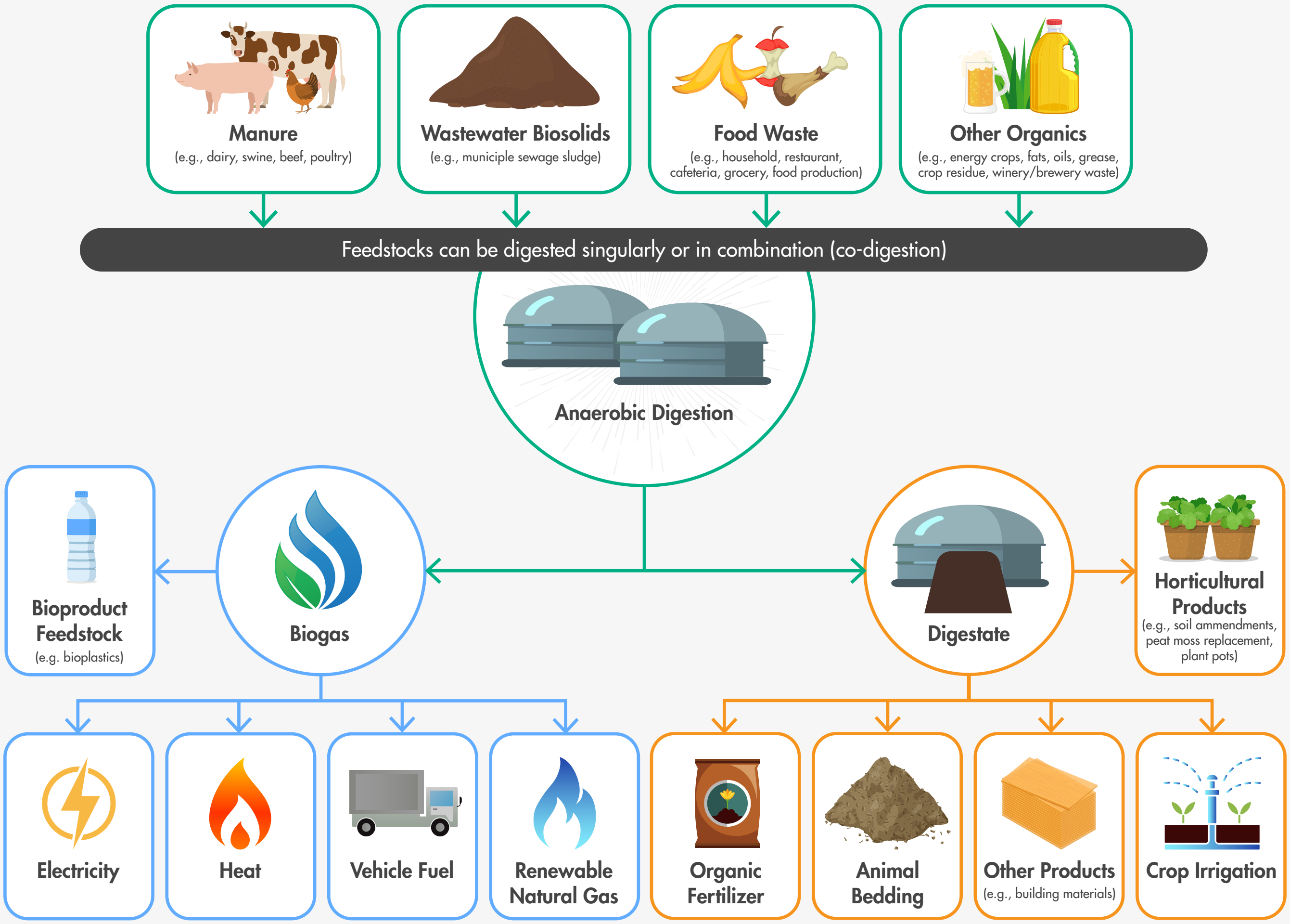


FIGURE 12: Diagram of anaerobic digester inputs and outputs.

Source: EPA. https://www.epa.gov/agstar/how-does-anaerobic-digestion-work.

Cost is also a significant barrier to adoption. Up-front capital investment costs can remain high,[155] and the operation and management of digesters represent both a financial and a practical burden for feedlot operators.

If barriers associated with manure collection, cost, and operation can be overcome, anaerobic digestion could significantly reduce emissions from manure. In such a breakthrough scenario, anaerobic digestion of all manure that is not currently composted could reduce manure emissions by roughly 34 percent.[156]

POLICY RECOMMENDATIONS

From cover cropping to feed additives, substantial opportunities remain to mitigate GHG emissions from US beef production. Yet all these practices require further R&D, regulatory approval, or economic incentives to enable widespread adoption.

Fund Research and Development of Breakthrough Technologies

The federal government has long been a major driver of agricultural innovation through the R&D funded and conducted by the USDA. This federally supported innovation has increased agricultural production while reducing the land use of US agriculture and producing fewer emissions per unit of agricultural product. Although the federal government already funds R&D aimed at improving beef production systems, increasing federal spending on agricultural R&D will be necessary to drive the decarbonization of the sector. Technological breakthroughs would not only reduce the cost and improve the effectiveness of existing practices like applying nitrification inhibitors to cropland but also expand their total mitigation potential, reducing beef's carbon footprint up to an additional 30 percent.

The federal government should fund R&D targeting the following technologies:

- **Enhanced root crops** that can sequester more carbon without reducing yields. The National Academies of Sciences, Engineering and Medicine estimates that $40—$50 million per year for at least 20 years would be needed to conduct the research required to commercialize enhanced root crops.[157]

- **Feed additives** that can limit methane emissions from enteric fermentation. The USDA National Institute of Food and Agriculture[158] and the Agricultural Research Service currently fund research on feed additives.[159] Expanding research to improve the effectiveness of feed additives in pasture-based systems could dramatically reduce long-term methane emissions from beef cattle.

- **Breeding**, including genomic breeding, to improve feed efficiency and disease resistance of beef cattle. Existing USDA programs like the Agricultural Genome to Phenome Initiative (AG2PI)[160] could effectively fund and conduct such research. The initiative was authorized for funding in the 2018 Farm Bill but has received minimal funding to date.

- **Anaerobic digesters** that can be used to break down beef cattle manure despite its low moisture content. Part of this research could investigate designing and demonstrating ways to remove manure from beef cattle facilities, such as by using feed lanes, that would facilitate manure collection and anaerobic digestion.[161]

Support Adoption of Existing Mitigation Practices

The federal government has several mechanisms for supporting agricultural producers in adopting technologies and practices that improve environmental outcomes. These include the Environmental Quality Incentive Program (EQIP),[162] the Conservation Technical Assistance Program (CTA),[163] and the Conservation Stewardship Program (CSP)[164] operated by USDA's Natural Resource Conservation Service (NRCS), as well as tax credits, discounts on federal crop insurance, and regulations.

To incentivize the adoption of low-carbon beef technologies, Congress should:

- **Increase funding for NRCS conservation programs** like EQIP, CTA, and CSP. NRCS programs already support most low-carbon beef practices, such as the use of nitrification inhibitors, cover crops, and silvopasture, but are oversubscribed.[165] Increasing top-line funding could also open incentive funds for practices like AMP grazing and cropland grazing practices, effectively increasing existing NRCS conservation incentives aimed at beef production.[166]

- **Establish a federal manure management program** to award grants or other support for non-anaerobic digester manure management practices that reduce GHG emissions. Such a program could be modeled after the California Department of Food and Agriculture's Alternative Manure Management Program,[167] which has been successful at incentivizing shifts in manure management at dairy facilities.

- **Support pilot or experimental anaerobic digester projects** on beef cattle operations. This can be done through multiple paths: reestablishing an investment tax credit for anaerobic digesters and other nutrient recovery projects, as proposed in Senators Brown and Roberts' Agricultural Environmental Stewardship Act;[168] creating a manure transport program to ensure that smaller operations can transport manure to nearby digesters, similar to an existing program in Maryland; and expanding coverage of clean fuel standards, similar to California's Low Carbon Fuel Standard, which incentivize investment in the renewable natural gas that anaerobic digestion can produce.[169]

- **Establish a rebate program to incentivize the purchase of precision farming equipment** such as variable-rate applicators that could reduce emissions from feed crop production. A rebate program could help extend incentives to producers who either require greater financial assistance or have been unable to procure support from existing programs due to oversubscription. This could be modeled after programs like California's Funding Agricultural Replacement Measures for Emissions Reductions (FARMER) program.[170]

Reform Agency Review of Low-Carbon Innovations

Methane-inhibiting animal products and genetic modification of plants or animals face high regulatory barriers to commercialization.

The US Food and Drug Administration (FDA) has classified products that reduce methane emissions from animals, such as 3-NOP, as animal drugs rather than food additives,[171] which typically include enzymes, probiotics, and other feed supplements.[172] The FDA's review of animal drugs is typically more extensive, costly, and time-consuming than for additives. The agency's review process for drugs typically takes 7—10 years,[173] with companies spending $30.5 million on average to receive approval.[174] For instance, the FDA process to review 3-NOP has taken more than four years and is expected to last several more.[175]

Instead, the FDA should:

- **Regulate methane-reducing animal products as feed additives/ingredients**, as the EU currently does.[176] The FDA would still review them to ensure that the products are safe for animals, workers, and consumers but require fewer years of research into how effective the products are at reducing methane emissions. The approval process for such additives typically takes three to five years.[177] The FDA may have the authority to make this change. A drug is defined as a product "intended to affect the structure or any function of the body of...animals,"[178] and methane inhibitors technically affect the microbes in the rumen. Nevertheless, congressional action to create a separate FDA track for environmentally beneficial feed products would provide researchers and product developers with greater regulatory certainty, helping foster innovation.

- **Prioritize review of products meant to reduce methane emissions.** The FDA has the discretion to prioritize types of applications. For example, it is currently prioritizing additives meant to mitigate African Swine Fever.[179]

The USDA also regulates the approval of genetically engineered crops and animals, which may be needed to develop enhanced root crops or to breed low-methane cattle.

The USDA should:

- **Regulate genetically engineered crops based on the risk they pose**. Although the USDA has loosened regulation for some types of genetically engineered crops, regulation remains too tied to the type of genetic modification rather than the risks it poses.
- **Create product-based regulation of genetically engineered animals** that determines the level of risk and regulation based on the familiarity of animal, trait, and intended environment.

Additional reforms will be necessary to improve other issues in the livestock and meat processing industries, such as worker safety, local pollution, and animal welfare. However, through a combination of support for research, regulatory reform, and producers adopting various practices and technologies, policy makers have the power to make lower-carbon-emitting, "clean" beef production a reality.

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