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The agricultural transition: Building a sustainable future

Sustainable farming is necessary for decarbonization. But to get the world to net zero, the agriculture sector must take action along the entire value chain.

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Executive summary

In 2020, we released our report *Agriculture and climate change,* which identified key actions the agricultural industry could take to support decarbonization.[1] For this report, our research has focused on how decarbonization measures have evolved, as well as on the key barriers to their adoption and the actions industry players and investors can take to support their uptake. At the same time, conversations about sustainable transitions have increasingly focused on agriculture's effects on nature and society beyond climate change. For example, agricultural land covers half of all habitable land and is responsible for 70 percent of freshwater withdrawals.[2] In addition, food systems are the primary driver of biodiversity loss around the world, and these systems have growing effects on biosphere integrity, human health, and food access.[3] While climate change remains the focus of this report, decarbonization and the actions to achieve it cannot be considered separately from their broader impacts on nature and society. Trade-offs and other benefits associated with decarbonization actions are highlighted throughout the report.

Achieving a 1.5° pathway will require actions that extend beyond the farm throughout the value chain. Chief among these actions are reducing food loss and waste, adopting dietary shifts, and adapting how we use arable land, all of which are critical to decarbonization and will help the industry meet global food needs while maintaining the livelihoods of farmers (Exhibit E1).

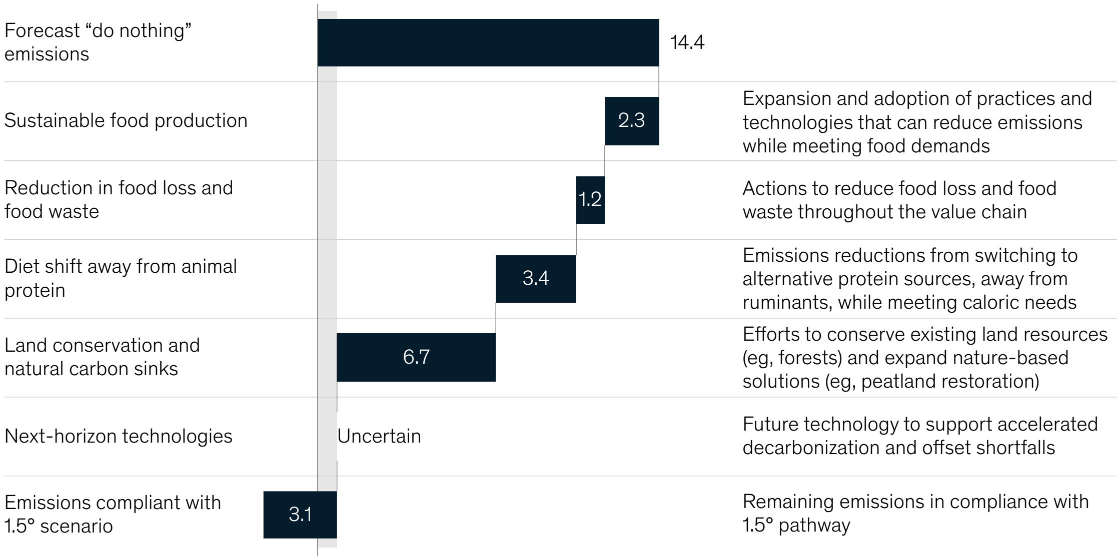
Tackling food waste. Approximately 30 percent of the world's food is lost or wasted every year.[4] Food loss and waste not only contribute an estimated 8 to 10 percent of global anthropogenic emissions[5] but also drive food insecurity and overproduction, the latter of which contributes in turn to nature degradation. It is estimated that food waste could be reduced by approximately 23 percent by 2050, which would account for approximately 0.7 metric gigatons (Gt) of CO_2 equivalent (CO_2e).[6] To achieve these reductions, we will need to better connect supply chains, improve preservation, adapt purchasing habits, and make more productive use of food loss or waste, creating opportunities for industrials across the value chain.

Shifting what we eat. Dietary shifts are already opening new markets and creating value for farmers and industrials. Producers and consumers can avoid releasing a substantial amount

Exhibit E1

Action in a handful of areas can allow global food and agriculture systems to decarbonize on track with a 1.5° pathway.

Levers to abate forecast agriculture production and LULUCF[1] emissions in 2050,
$GtCO_2e$[2] (GWP AR6 100Y[3])



Note: In sum, levers achieve emissions reductions slightly beyond 2050 compliance with the 1.5° pathway, leaving room to account for overlap in reductions potential and failure to meet targets.
[1] Land use, land-use change, and forestry.
[2] Metric gigatons of carbon dioxide equivalent.
[3] Global warming potential, as outlined in the 100-year scenario of the Intergovernmental Panel on Climate Change's *Sixth Assessment Report*.

of emissions by turning to alternative protein sources, including plant-based products and precision-fermented and cellular products that are nearly identical to animal protein products. For example, classic plant-based options emit 12 percent of the total greenhouse gases (GHG) emitted by cattle and have a lesser ratio of methane per kilogram of product.[7] Dietary shifts away from animal proteins could save nearly 640 million hectares of land, which could in turn be reforested or become a locus for other nature-based solutions.[8] Of course, in the case of alternative protein sources, trade-offs, including human health, food access, and farmer equity, are especially important and must be adequately considered as part of any transition.

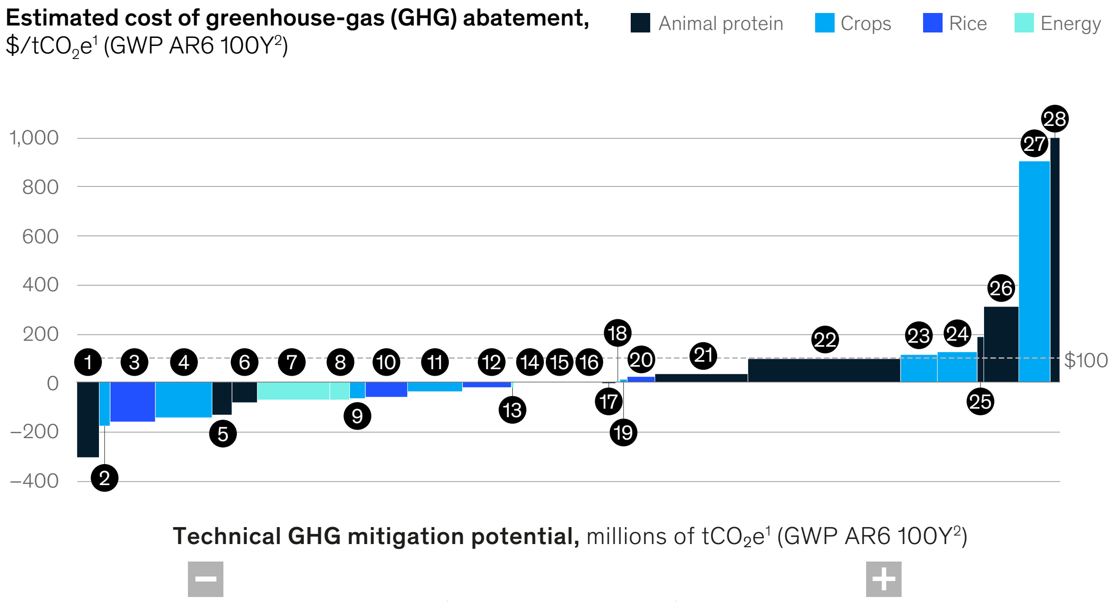
Addressing land use with nature-based solutions. Agricultural land covers approximately 4.9 billion hectares, or 38 percent of the world's terrestrial area, and is estimated to account for approximately 80 percent of global land-use change as land is cleared or converted for cropland, feed production, or grazing land.[9] Given this enormous land-use footprint, nature-based solutions, including conservation and restoration solutions, have the potential to abate 6.7 $GtCO_2e$ in 2050—approximately 80 percent of the total abatement potential.[10] The largest levers for achieving this potential concern improved forestry practices, especially forest restoration. Notably, adoption of many nature-based solutions will likely require increased land-use intensification to meet global food demand and adequate incentives for farmers to limit future land conversion.

Changing how we farm, the focus of this report, is critical to a successful transition. Building on our previous work, we have defined 28 measures that can support decarbonization on the farm while creating value for the industry and farmers (Exhibit E2). Together, these measures have an annual emission-reduction potential of approximately 2.2 $GtCO_2e$. Many of these measures can be implemented at little to no cost to the farmer and have benefits beyond emissions reductions, including yield and biodiversity uplift.

Twenty-eight measures can support decarbonization on the farm while creating value for the industry and farmers.

Exhibit E2a

A marginal abatement cost curve (MACC) shows the relative costs of identified decarbonization measures.



1	Increase concentrate-to-forage ratio	**−306**
2	Biologicals	**−177**
3	Direct seeding of rice	**−159**
4	Reduced overapplication of fertilizer	**−146**
5	Expanded adoption of technologies that increase livestock production	**−135**
6	Heat stress management	**−84**
7	Electrification of on-farm machinery	**−72**
8	Hydrogen power for on-farm machinery	**−71**
9	Variable-rate fertilization	**−64**
10	Improved rice paddy water management	**−59**
11	Nitrogen inhibitors on crop fields	**−37**
12	Improved rice straw management	**−23**
13	Improved fuel efficiency in fishing vehicles	**−22**
14	Biochar as a fertilizer	**0**
15	Improved animal health and disease treatments	**0**
16	GHG-focused breeding and genetic selection	**0**
17	Feed grain processing for digestibility	**1**
18	Conversion to hybrid and electric fishing vessels	**5**
19	Incorporation of cover crops	**10**
20	Sulfate fertilization of rice	**22**
21	Nitrogen inhibitors on pastures	**34**
22	Advanced feed additives	**99**
23	Conversion from flood to drip or sprinkler irrigation	**116**
24	Low- or no-tillage	**123**
25	Shift to a higher-fat diet	**188**
26	Large-scale anaerobic manure digestion	**311**
27	Enhanced efficiency fertilizers	**904**
28	Small-scale anaerobic manure digestion	**1,000+**

Note: The width of each bar on the horizontal axis reflects GHG mitigation potential for each lever; the vertical axis displays the average abatement cost ($/tCO$_2$e) for each lever; the total abatement potential is less than the full width of the marginal abatement cost curve (MACC) due to the potential for interaction between some levers.

[1] Metric tons of carbon dioxide equivalent.

[2] Global warming potential, as outlined in the 100-year scenario of the Intergovernmental Panel on Climate Change's *Sixth Assessment Report*.

Exhibit E2b

A marginal abatement cost curve (MACC) shows the relative costs of identified decarbonization measures. (continued)

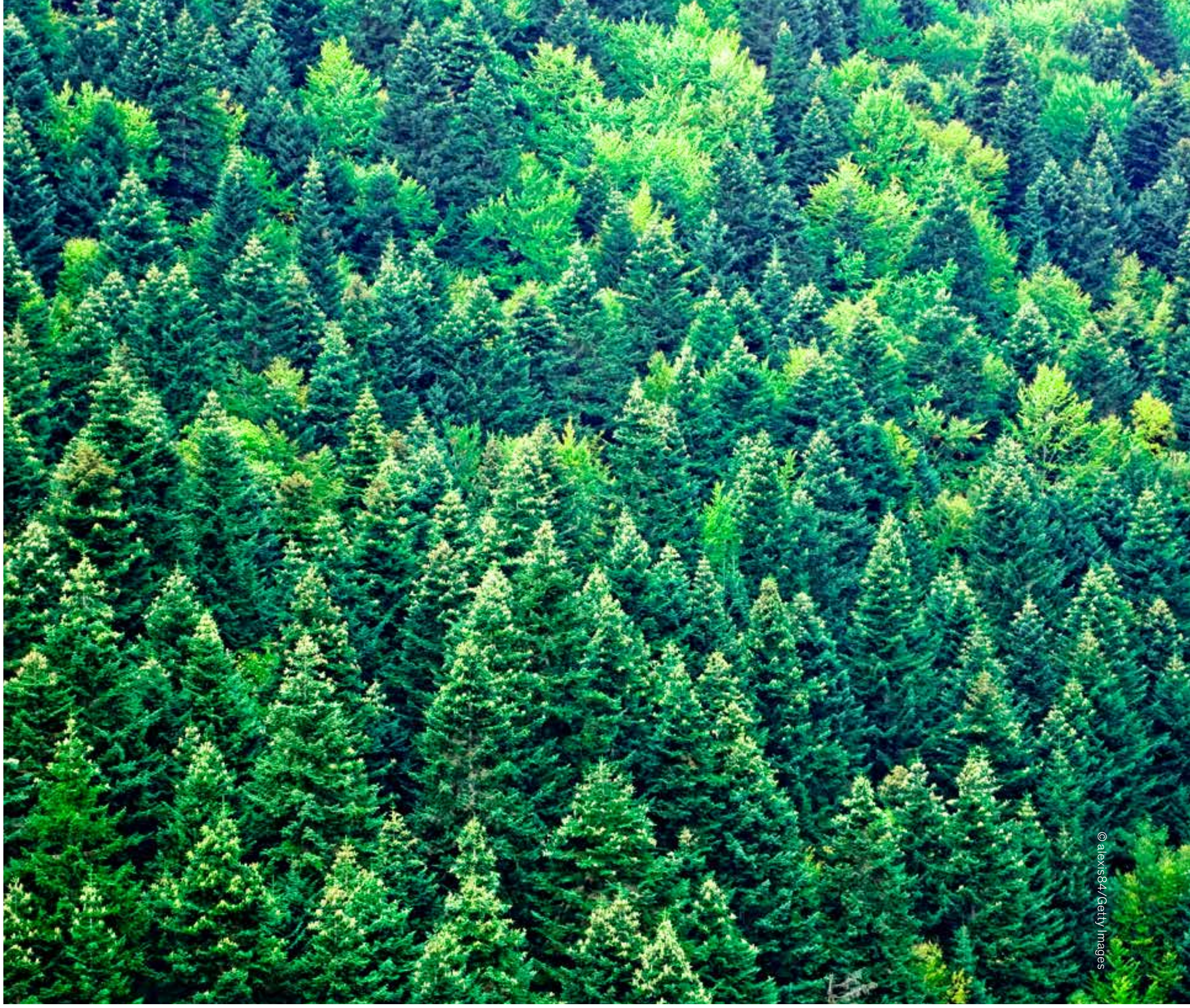
	Animal protein	Crops	Rice	Energy
GHG emissions, % reduction (vs 2050 “do nothing” emissions)	–23	–36	–59	–15
GHG emissions, amount of reduction in metric gigatons (Gt) of CO_2e (vs 2050 “do nothing” emissions)	1.1	0.6	0.4	0.2

Although a 1.5˚ pathway exists and can create value for farmers and the broader industry, meaningful barriers are preventing the adoption of decarbonization solutions at scale. Farmers are central to the sustainability transition, but they do not yet have sufficient incentives to adopt new methods and technologies. Emissions tracing and other actions require new, innovative solutions to facilitate decarbonization. And there is much room to grow in helping farmers overcome challenges in scaling their operations and maintaining profitability.

The findings in this report can guide food and agriculture organizations as they transition to increased sustainability. Each intervention should be tailored to its specific context, but broadly speaking, change requires the following:

- *financial incentives to spur farmer action,* whether through carbon markets, green premiums, subsidies, rebates, or other green-financing mechanisms
- *ecosystem collaboration and improved tracking and traceability* to bring solutions to market and support monetization of on-farm practice changes and purchaser decision making
- *research and investment to bend the cost curve* to reduce adoption costs for existing solutions and support the development and scale-up of new technologies

The food and agriculture value chain has a chance to create a more sustainable ecosystem that feeds a growing planet while maintaining the livelihoods of farmers. With tailored and concentrated action, industry players, policy makers, and investors can accelerate the path to this future while enabling their own growth.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Momentum for decarbonization in agriculture

Significant progress has been made in decarbonizing industries and sectors across the world, but unless greenhouse-gas (GHG) emissions are steeply reduced in the coming decades, global temperatures will rise 2.0°C or higher above preindustrial levels during the next century, according to the 2022 *Sixth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC).[11] Four of the nine planetary boundaries, including land-system change and species extinction, are already in or beyond the zone of uncertainty as defined by the Stockholm Resilience Center.[12] Furthermore, the agriculture industry alone accounts for nearly a quarter of global emissions.[13]

In response, consumers, investors, policy makers, and nongovernmental organizations (NGOs) are increasingly demanding affordable, sustainable products that meet the world's nutritional needs. These demands are creating momentum and opportunity for food and agriculture industrial companies, start-ups, and investors to meet these needs in a climate-resilient, profitable manner.

Consumers are directing investor interest as they become more conscious of the environmental impacts of their food, especially in the West. According to a 2021 survey of consumers, approximately 30 percent of European and US consumers plan to spend more on environmentally friendly products.[14] Further, many consumers are shifting their diets to incorporate plant-based dairy and meat alternatives, and "flexitarian" diets are on the rise. Investors are taking notice, and food and agriculture companies are benefiting from shifts in investment flows. Despite continued decreases in overall venture capital (VC) investments, agtech investments saw modest growth between the second and third quarters of 2022.[15]

At the same time, policy makers and NGOs across the globe are supporting transparent tracking and other measures to accelerate a more sustainable future. In March 2022, the US Securities and Exchange Commission proposed rule changes related to emissions disclosures, including Scope 3 emissions, which could increase scrutiny on sourcing and encourage organizations to provide consumers with additional visibility. Other policies support the adoption of low-carbon and nature-positive farming practices. For example, the Inflation Reduction Act in the United States has assigned $40 billion for advancing regenerative agriculture practices such as cover cropping and agroforestry, with additional funding for sustainable solutions from the US Department of Agriculture (USDA).[16] And NGOs are supporting organizations in setting targets and ensuring robust tracking of these goals (see sidebar "Forest, land, and agriculture guidance from the Science Based Targets initiative").

Forest, land, and agriculture guidance from the Science Based Targets initiative

Science Based Targets, a leading organization for climate targets, recently launched its forest, land, and agriculture (FLAG) guidance to expand coverage and support organizations in setting science-based targets related to emissions.[1] Developed in collaboration with private organizations across the food and agriculture value chain, the guidance accounts for land-use-change emissions, land-management emissions, and carbon removals.

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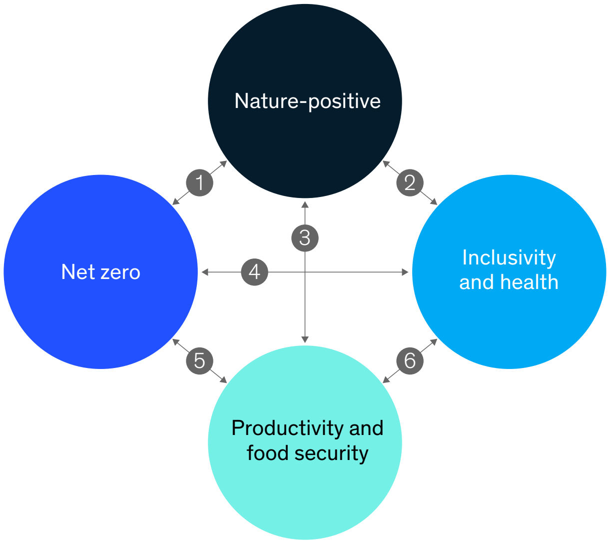
[1] "FLAG Science Based Target Setting Guidance launch," Science Based Targets, September 28, 2022.

Players in food and agriculture systems need to keep multiple primary goals in mind to deliver affordable food at scale while limiting their impact on the planet (Exhibit 1). However, taking action toward any one of these goals can be a complex balancing act: momentum on decarbonization and nature-positive action cannot be considered separately from humanitarian needs or feeding the planet.

Today, many food and agriculture players are focused on the trade-offs involved in implementing new decarbonization measures. On the one hand, many solutions that reduce GHG emissions can negatively affect productivity and food security. On the other hand, decarbonization actions can also accelerate progress toward other goals. For example, farmers who implement decarbonization practices can improve soil health and increase water retention, resulting in higher yields while restoring the biosphere. With this in mind, decarbonization solutions need to be considered in the context of their broader impact.

Exhibit 1

In many situations, players must negotiate trade-offs between the four main goals of the agriculture system.



① Raising livestock in feedlots reduces greenhouse-gas intensity but may have negative effects on soil and aquatic health.

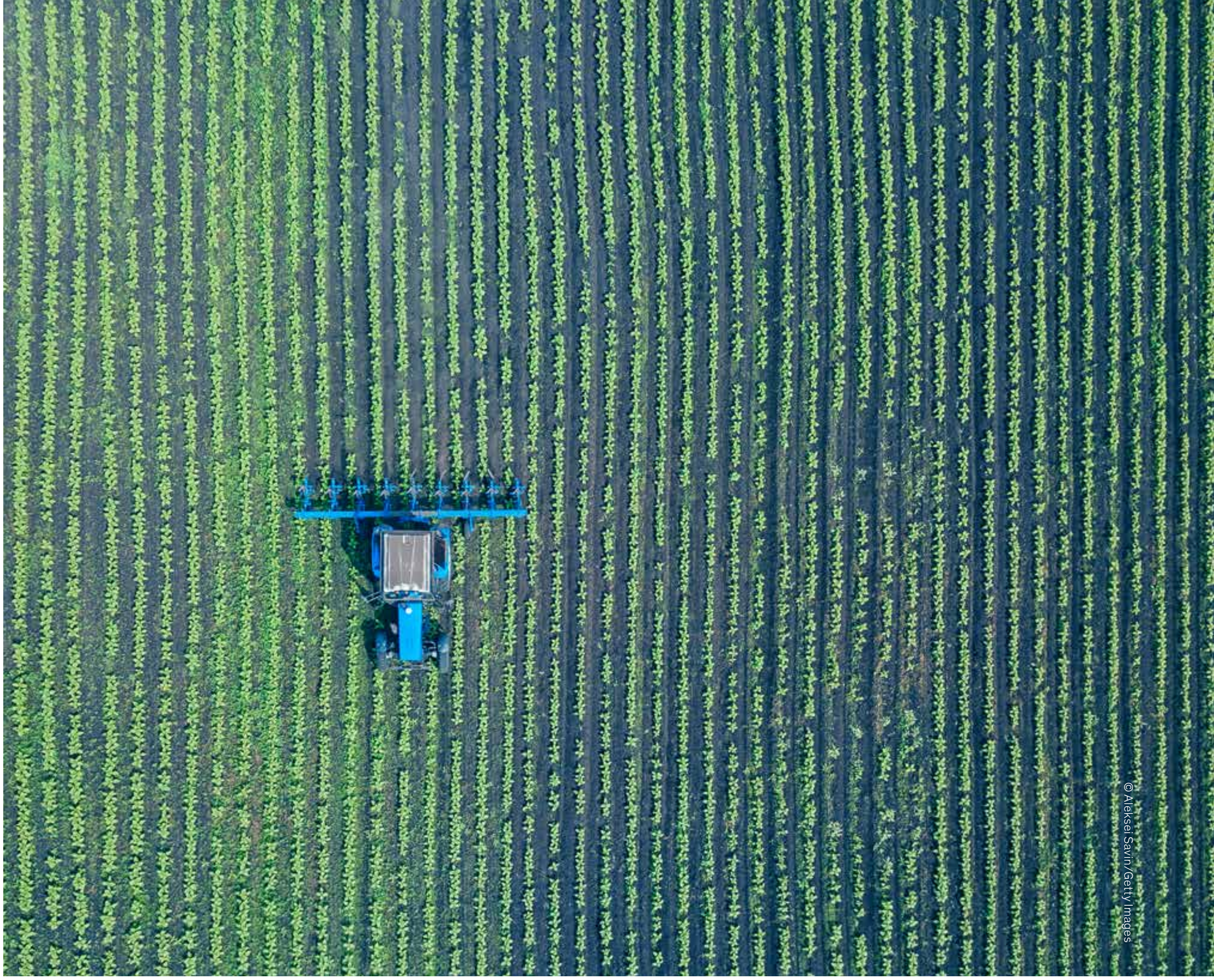
② Desired or demanded nature-positive practices may be more expensive or difficult to verify for smallholder farmers.

③ Nature-positive practices and input use may reduce yield and yield stability.

④ Validation and verification requirements are likely limiting for smallholder farmers (eg, protocols or technology needs).

⑤ Conserving forest land avoids carbon loss but would limit the amount of arable land and constrain food production.

⑥ Industrialized agriculture may increase food availability in some countries, but technology and financing are not universally available.



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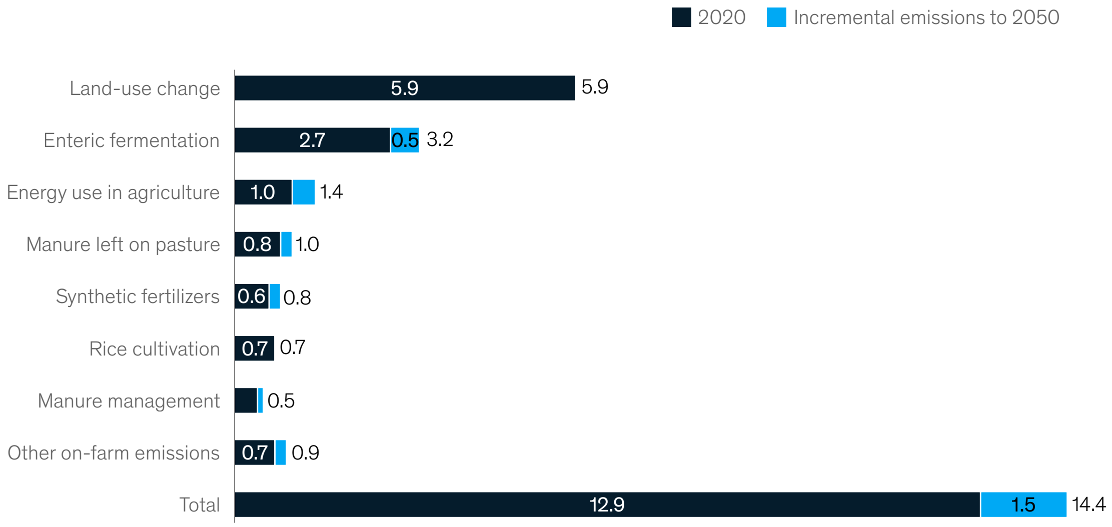
A revised perspective on 1.5° pathways

Many organizations, such as the IPCC and the World Wide Fund for Nature,[17] and numerous scholars have published perspectives on and pathways to 1.5°. This report is intended to provide our current perspective on the agriculture sector, which is seen as particularly difficult to abate. A wide variety of emissions sources are associated with agriculture; however, three major sources combined account for nearly 74 percent of the total, making them excellent targets for action (Exhibit 2):

Exhibit 2

The top three emissions sources in agriculture account for three-quarters of its total emissions.

Projected greenhouse-gas emissions from agriculture production,
Global emissions, $GtCO_2e$[1] (GWP AR6 100Y[2]), by emissions source



Note: Figures may not sum, because of rounding.
[1] Metric gigatons of carbon dioxide equivalent.
[2] Global warming potential, as outlined in the 100-year scenario of the Intergovernmental Panel on Climate Change's *Sixth Assessment Report*.
Source: Food and Agriculture Organization of the United Nations; Intergovernmental Panel on Climate Change's *Sixth Assessment Report* (IPCC AR6); Pierre Friedlingstein et al., "Global carbon budget 2020," *Earth System Science Data*, December 2020, Volume 12, Number 4

— **Land-use change** refers to emissions associated with land conversion for agriculture. The most common source of these emissions is deforestation, and the majority of land is used to feed and raise livestock: grazing lands account for 26 percent of the planet's ice-free land, and another 33 percent is used to produce livestock feed.[18]

— **Enteric fermentation** refers to the methane emitted by cattle, sheep, goats, and other ruminants during the digestion process. This methane significantly increases the emissions footprint of ruminants relative to other protein sources.

— **Energy use in agriculture** refers to the on-farm emissions associated with energy production, primarily fuel combustion and electricity generation.

To address these emissions sources, we identified interventions to achieve net-zero emissions and sized them against the baseline of agricultural emissions developed by the Food and Agriculture Organization of the United Nations (FAO), using the tier-one methods of the IPCC guidelines for national GHG inventories (additional detail can be found in the appendix). Although the impact of interventions such as land-use change, on-farm practices, and dietary shifts will likely vary based on incentives and policy shifts, each will be important to consider to create sustainable agricultural systems, regardless of warming scenario.

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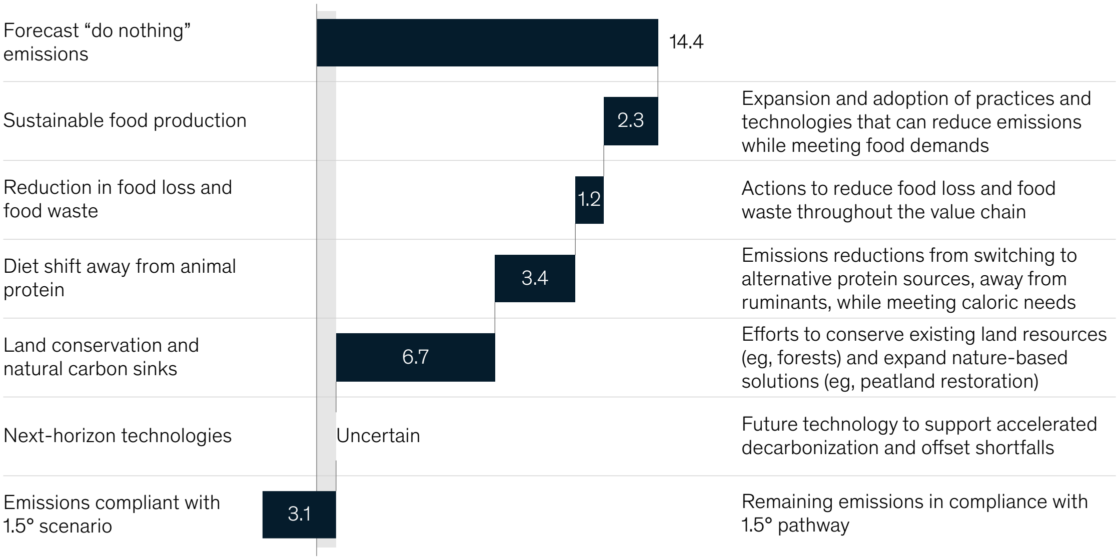
Measures to effect change

To remain on a 1.5° pathway, agriculture will have to cut its overall emissions from 14.4 metric gigatons (Gt) of CO_2 equivalent (CO_2e) to 3.1 $GtCO_2e$ by 2050—almost 80 percent (Exhibit 3). Luckily, there are a number of solutions that can help drive meaningful progress toward decarbonization and sustainability, such as reducing food loss and food waste, shifting diets (primarily away from animal protein), and implementing nature-based solutions. Further innovation and commercialization of next-horizon technologies can provide additional reductions beyond what is estimated.

Exhibit 3

Action in a handful of areas can allow global food and agriculture systems to decarbonize on track with a 1.5˚ pathway.

Levers to abate forecast agriculture production and LULUCF[1] emissions in 2050, $GtCO_2e$[2] (GWP AR6 100Y[3])



Note: In sum, levers achieve emissions reductions slightly beyond 2050 compliance with the 1.5° pathway, leaving room to account for overlap in reductions potential and failure to meet targets.

[1] Land use, land-use change, and forestry.

[2] Metric gigatons of carbon dioxide equivalent.

[3] Global warming potential, as outlined in the 100-year scenario of the Intergovernmental Panel on Climate Change's *Sixth Assessment Report.*

Decarbonizing the world's food and agriculture systems will change the way we farm and augment progress in the final area for action—and the focus of this report—sustainable food production. Our estimates indicate that action in these areas could reduce emissions sufficiently to achieve a 1.5˚ pathway, with some overshoot to account for potential overlap.

Tackling food waste

Approximately 30 percent of the world's food is lost or wasted every year.[19] The FAO estimates that around 14 percent of food is lost during upstream production,[20] and the UN Environment Programme's 2021 Food Waste Index Report estimates that a further 17 percent of food was wasted downstream in retail, food service, and households.[21] Food loss and waste not only contribute an estimated 8 to 10 percent of global anthropogenic emissions[22] but also drive food insecurity and overproduction.

On a percentage basis, food loss is highest in lower-income regions where supply chains are less developed and preservation systems are less robust. For example, loss rates in Western Africa are as high as 24.8 percent versus 6.5 percent in Western Europe.[23] That said, food loss can also be high in developed economies, driven by price volatility, high consumer standards, and production surplus. Food waste rates during consumption and distribution tend to be higher in high-income geographies: around 29 percent in North America versus 5 percent in South and Southeast Asia, for example.[24] Globally, the majority of food waste occurs in households as a result of overbuying, consumers' psychological distance from the waste they create, and other factors.[25]

It is estimated that food waste could be reduced by approximately 23 percent by 2050, which would lead to an emissions reduction of approximately 0.7 $GtCO_2e$.[26] In addition, food loss reductions of 17 percent could be achieved by 2030,[27] which could contribute an additional 0.5 $GtCO_2e$ to emissions reductions.[28] Reducing food loss and waste carries benefits beyond climate change as well. For example, reducing them by a combined 50 percent overall by 2050 would prevent agricultural conversion of land the size of Argentina and reduce freshwater use by approximately 13 percent.[29]

Achieving these reductions will require action across the value chain to better connect supply chains, improve preservation, adapt purchasing habits, and make more productive use of food loss or waste. Organizations are mobilizing to address both food loss and food waste. For example, the UN's Sustainable Development Goal 12.3 is to "halve per capita global food waste at the retail and consumer levels" by 2030.[30] And the 123 Pledge was introduced at the 2022 UN Climate Change Conference (COP27) to accelerate efforts to reduce food loss and waste.[31]

Addressing land use with nature-based solutions

Innovating how we use our limited land resources can create new opportunities to achieve net-zero goals. Current food and agriculture systems are a leading cause of land-use change. Agriculture alone is estimated to account for approximately 80 percent of global land-use change, which has a profound impact on carbon release and also negatively affects biodiversity and ecosystems.[32] The UN's International Union for Conservation of Nature (IUCN) has identified agriculture as a threat to more than 19,000 species facing a high risk of extinction, making it the single largest driver of accelerating biodiversity loss.[33]

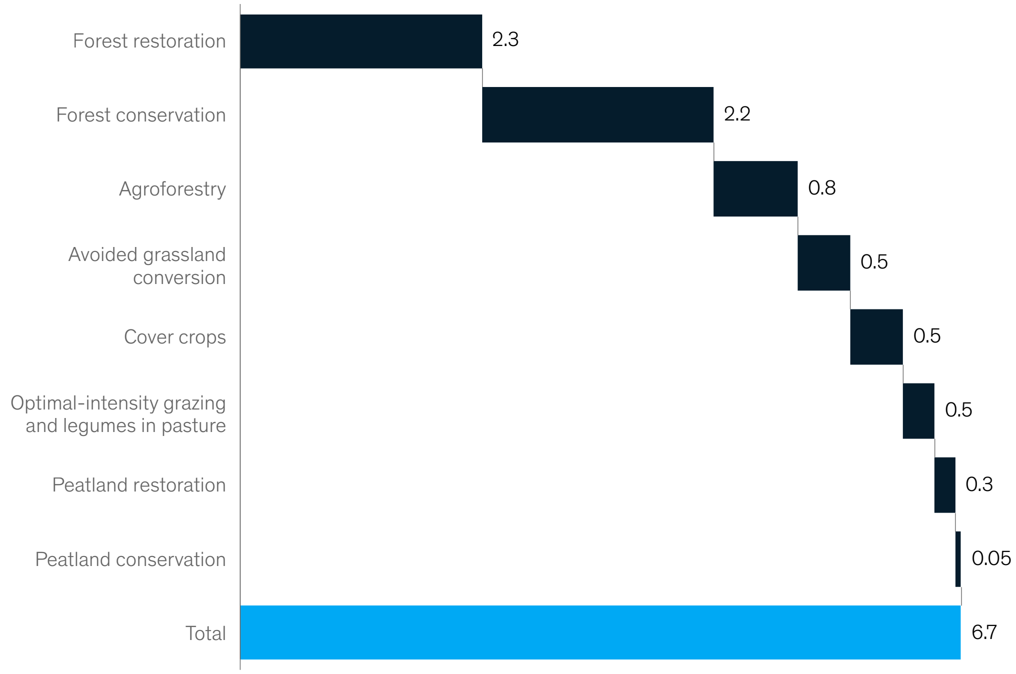
Altogether, nature-based solutions, including conservation and restoration solutions, have the potential to abate 6.7 $GtCO_2e$ by 2050 (Exhibit 4).[34] Improved forestry practices account for approximately 80 percent of this potential. Restoration levers offer the greatest potential, yet the importance of protecting carbon-dense regions, such as peatlands and tropical forests, cannot be overstated. Land degradation only makes restoration efforts more difficult, and restoration tends to be more expensive than conservation.

Agriculture-specific innovations to directly address land use while feeding a growing population are emerging. Farmers are thinking about how they can get more out of their land and use it for multiple purposes, such as planting trees or adding solar panels in cropland and pastures (see sidebar "Integrated farming systems").

Exhibit 4

Restoration and conservation are the most effective levers for abating land-use emissions, in addition to a number of others.

Feasible greenhouse-gas abatement potential of restoration and avoidance levers, $GtCO_2$/year,[1] 2050



Note: Figures do not sum, because of rounding.
[1] Metric gigatons of carbon dioxide per year.
Source: IPR Nature Scenario; McKinsey TRAILS Solution

Notably, many of these technologies will require limited future conversion of land, which will in turn likely require land-use intensification to meet global food demand. Farmers will need adequate incentives to limit their land use in favor of conservation and restoration. Incentives from carbon and nature markets, industry players, and policy makers are beginning to emerge but will need to continue to scale:

— Carbon and nature markets today are supporting farmers in adopting nature-based solutions such as cover cropping and no-till farming, for which they can generate and sell carbon credits. In 2021, the share of nature-based credits in voluntary markets increased by nearly 20 percentage points, with a clear price premium.[35]

— Policy makers are also beginning to respond. For example, the USDA Conservation Reserve Program continues to pay farmers an annual rental fee to stop farming on environmentally sensitive lands.[36] In addition, the Inflation Reduction Act in the United States includes $5 billion specifically for climate-smart forestry and wildlife protections. Brazil has pledged to restore 15 million hectares of degraded pastureland, and China has pledged to increase forest stock by six billion cubic meters from the 2005 level.

Integrated farming systems

Silvopasture and agroforestry are practices that integrate trees into pasture and cropland to meaningfully benefit environmental and production goals. For example, agroforestry can provide 45 to 65 percent more benefits for biodiversity than standard agricultural landscapes, and silvopasture sequesters five to ten times as much carbon as standard pastures.[1] In addition, trees can make farms more resilient by protecting crops and livestock from the sun. They also require fewer inputs and improve soil health while providing farmers another revenue stream.[2]

Agrovoltaics—the practice of incorporating solar panels on arable land—has the potential to sustainably increase agricultural yields, reduce water use, create additional revenue, and promote equity for small-scale farmers.[3] Solar panels can provide energy directly to farms, reducing their dependency on fossil fuels and encouraging energy independence for small-scale farmers in developing communities; excess energy can be sold to the grid. The shade provided by the panels can make farms more water efficient and provide valuable shade for livestock, leading to greater productivity for both crop and animal yields.

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[1] Jerônimo Boelsums Barreto Sansevero, Renato Crouzeilles, and Pedro Zanetti Freire Santos, "Can agroforestry systems enhance biodiversity and ecosystem service provision in agricultural landscapes? A meta-analysis for the Brazilian Atlantic Forest," *Forest Ecology and Management*, February 2019, Volume 433; "Silvopasture," Project Drawdown, accessed May 11, 2023.

[2] "Soil health," National Agroforestry Center, US Department of Agriculture, accessed May 11, 2023.

[3] Chad W. Higgins, Ganti S. Murthy, and Kyle W. Proctor, "Agrivoltaics align with Green New Deal goals while supporting investment in the US' rural economy," *Sustainability*, December 2020, Volume 13, Number 1.

- Large private-sector players are also making direct changes. For example, COP27 saw 14 agricultural commodity partners commit to act by reducing emissions from land-use change and deforestation.[37]

Considerations for land use extend beyond the need to feed a growing population. As other industries make sustainable transitions, demand for crop inputs may grow. An estimated 40 percent of the US corn crop is used in biofuels, along with 30 percent of the soy oil produced in the United States.[38] Biobased feedstocks for production of basic chemicals, which are often derived from corn and other agriculture inputs, are seeing increasing traction. Although alternative, lower-input feedstocks may support growing demand, effective cross-industry decarbonization will rely on careful consideration of the land-use and food security impacts associated with adoption of these technologies.

Shifting what we eat

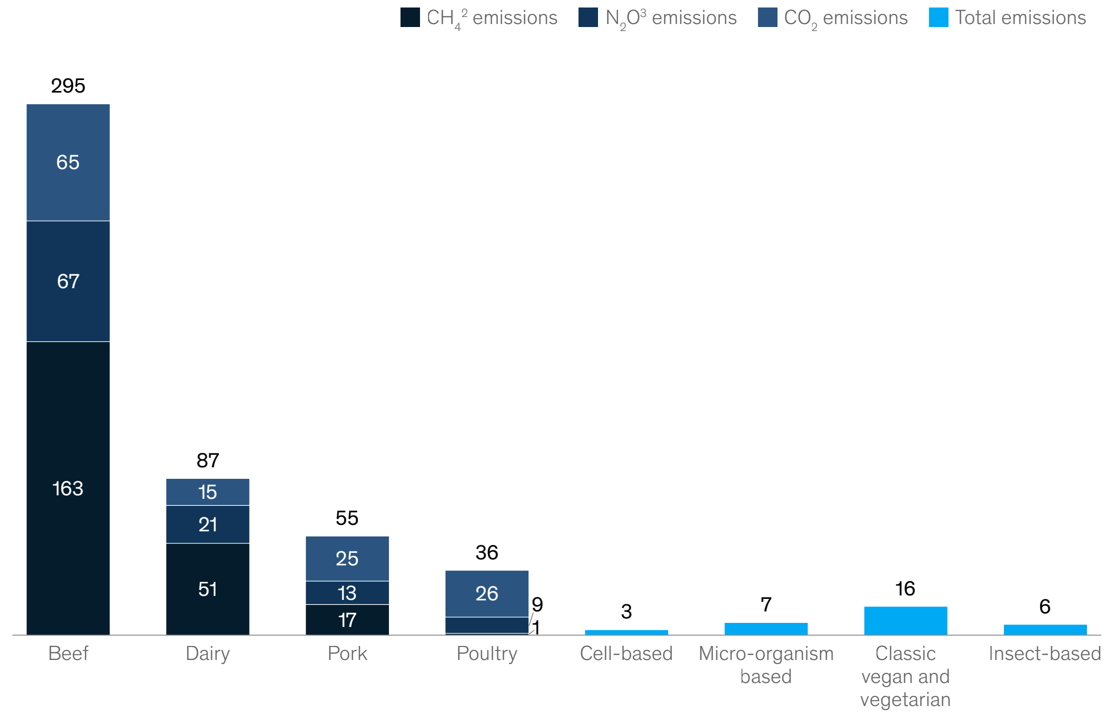
Changes in the composition of human calorie consumption by shifting diets is an opportunity to limit methane emissions from livestock. These methane emissions increase atmospheric temperature approximately 80 times more than CO_2 on a 20-year outlook, but methane has a shorter atmospheric lifetime than other GHGs, making it an effective target for reducing global temperatures quickly. Animal-sourced products supply 18 percent of the calories consumed by humans today,[39] and that proportion continues to rise—especially in developing countries, where demand for animal meat is expected to grow by as much as 74 percent.[40] In this high-demand environment, producers and consumers can avoid a substantial amount of emissions by turning to alternative protein sources, including classic plant-based products and precision-fermented and cellular products. For example, classic plant-based options emit about 5 percent of the total GHGs emitted by cattle and have a lesser ratio of methane per kilogram of product (Exhibit 5).[41]

In addition, alternative protein sources have smaller physical footprints and consequently limit future land conversion while creating opportunities for sequestration. For example, one kilogram of beef protein requires an estimated 326 square meters of land versus four for plant-based options, 12 for poultry, and only three for cell-based.[42] Dietary shifts away from animal proteins could save nearly 640 million hectares of land, which could in turn be reforested or provide a locus for other nature-based solutions.[43]

Exhibit 5

Conventional protein sources, especially ruminants, have significantly larger emissions intensities than alternatives.

Current life cycle emissions intensity, kg of CO_2e/kg protein[1]



[1] Kilograms of CO_2 equivalent per kilogram of protein.
[2] Methane.
[3] Nitrous oxide.
Source: ClimateWorks Foundation Global Innovation Needs Assessment (GINA), Protein Diversity; Food and Agriculture Organization GLEAM (Global Livestock Environmental Assessment Model); J. Poore and T. Nemeck, "Reducing food's environmental impacts through producers and consumers," *Science*, June 2018, Volume 363, Number 6429; "Meat: The future series - Alternative proteins," World Economic Forum, January 2019

Even modest diet changes such as “flexitarianism,” or semi-vegetarianism, can improve emissions outcomes. If 50 percent of the global population reduced their daily consumption of animal-based proteins to 60 grams (about 150 calories of beef), 2.2 $GtCO_2e$ could be mitigated.[44] In conjunction with emission-reduction methods for conventional protein, such as anaerobic digestion, this shift could significantly decrease global emissions from protein production.

The market for alternative proteins is no longer nascent. Market participants have found success across a broad spectrum of categories, and between 2019 and 2022, dollar sales grew by 44 percent, including 7 percent between 2021 and 2022.[45] In spite of this overall growth, stakeholders must overcome a number of challenges to further enhance adoption of alternative proteins. Successful alternative proteins have sensory profiles—most of all taste and texture—that consumers enjoy. Palatability is particularly important given that plant-based products remain more expensive than meat, due in part to high initial investments and limited availability for the production supply chain. Policies can support consumer adoption; for example, the European Union’s Farm to Fork strategy aims to increase the availability of alternatives.

In making these dietary shifts, producers and consumers must first consider their impact on human health and livelihoods. In some cases, these impacts are positive. For example, research suggests that encouraging citizens to shift their diets toward alternative proteins could reduce dietary mortality by up to 7 percent, with the largest impact in upper-middle-income countries.[46] However, research also highlights the need to consider the nutritional impacts of alternatives in addition to their environmental impacts. For example, tofu is the only plant-based alternative to traditional protein sources that has a comparable digestibility and amino acid profile.[47] In addition, sufficient protein must remain available and affordable to consumers. The shift to alternatives will likely need to be led by wealthier nations, which can afford such solutions, rather than by developing nations, which may instead focus on improvements in animal productivity.[48]

Dietary shifts away from animal proteins could save nearly 640 million hectares of land, which could in turn be reforested or provide a locus for other nature-based solutions.

Innovating to drive further progress

Further progress toward achieving sustainability goals will require additional innovations and technical solutions beyond what is commercially feasible today. We identified four thematic areas of agtech innovation: decarbonizing inputs, digital agriculture, livestock enteric emissions reductions, and novel production methods.

Decarbonizing inputs

This refers to interventions to reduce emissions from the production or application of inputs. For instance, agricultural inputs, such as fertilizers, pesticides, herbicides, and fungicides, generate an estimated 1,188 metric megatons (Mt) of CO_2e in emissions across the value chain, from production to application.[49] New techniques to reduce emissions across the entire value chain focus on three main areas:

— *reducing emissions from production,* such as through the use of clean ammonia, which can mitigate approximately 99 percent of emissions from production[50]

— *reducing application rates of chemical inputs* such as biologicals

— *improving crop uptake and resistance,* including through gene editing

Digital agriculture

One of the least digitalized industries in the United States, agriculture could benefit from new tools and techniques to help leverage data or analytics in service of sustainable decision making.[51] Digital solutions in agriculture such as the following could provide an ROI for growers and the environment alike:

— *farm management software* to improve operational efficiency

— *carbon verification and monitoring tools* to measure carbon emissions and sequestration, monitor and optimize irrigation systems, and estimate sustainability impact

— *precision agriculture hardware* to provide real-time soil measurements and reduce inputs

— *remote-sensing technologies* to monitor crop growth and reduce broad pesticide application

— *agribusiness marketplaces* to provide greater insight into food safety and traceability

— *farm robotics and automated and electrified machinery* to reduce labor needs, optimize field operations, and reduce input usage and operating costs

Livestock enteric emissions reductions

Novel methods are emerging to reduce enteric emissions in livestock, particularly in grassland-based systems. Most current interventions focus on reducing emissions from cows raised in feedlots, where their feed, diet, and conditions are most controllable. However, emissions from feedlots account for a small portion of livestock emissions, given their low prevalence and relatively efficient production mechanisms.[52] New interventions can thus focus on reducing enteric emissions from livestock raised in grassland or mixed systems, where cattle might be centrally handled only once or twice a year for weighing and treatment and where their feed rations are unpredictable and uncontrollable.

Potential interventions include the following:

- *methane vaccines* to suppress methanogenesis, the process that produces methane
- *rumen-modifying microbes*, which can be added to water sources or as a silage inoculant in mixed systems[53]
- *novel delivery methods*, such as encapsulation technologies, to incorporate feed additives in grassland or mixed systems

Novel production systems

The aforementioned interventions largely represent mechanisms to reduce emissions within the current agricultural production system. However, there is growing movement toward novel methods that represent a fundamental change in the way we grow our food:

- *Controlled-environment agriculture (CEA)*, including vertical farms, allows for controllable growing conditions and can decrease water, land, and chemical input consumption per acre. But CEA demands significantly more energy than conventional farming systems.
- *Land-based aquaculture* can enable production closer to areas of demand and achieve up to 50 percent reductions in emissions relative to traditional open-net-pen systems if powered by renewables.[54]

* * *

In each of these areas, there's no shortage of innovations that have the potential to reduce emissions and change the way our food is grown. Every day, new advances in science, software, and computing push the frontier of possibilities for a new food system.

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Changing how we farm

Adapting how we farm, the focus of this report, will be critical to a successful transition and could support estimated annual emissions reductions of 2.2 $GtCO_2$. Action will be required across farming ecosystems large and small, including all forms of crops and livestock. Today, farmers are adopting practices that decarbonize and reduce impacts on planetary boundaries while improving their bottom lines, such as optimizing fertilizer use and managing livestock heat stress. More forward-thinking farms are adopting newer technologies, such as anaerobic digestion and electrified equipment, to drive further impact.

While many strategies have benefits in addition to reducing emissions and can be implemented at little to no cost to the farmer, economics remains a key barrier to at-scale adoption. Further investment, education, and development from industrials, start-ups, and financial institutions will support accelerated uptake. The following chapter details measures to reduce on-farm emissions, barriers limiting adoption, and opportunities for collaboration to drive adoption.

Sustainable changes in food production

The primary focus of this report is on sustainable food production, for which we have identified 28 measures that can support on-farm decarbonization in line with the 1.5° pathway described in the IPCC's *Sixth Assessment Report*. Altogether, on-farm decarbonization has an annual emission-reduction potential of approximately 2.2 $GtCO_2$ (see "Measures for supporting decarbonization and sustainability impacts: Deep dives" in appendix), with the majority of mitigation coming from the top 15 measures (Exhibit 6).

Much has changed since our previous publication, including the addition of five new measures that can play an active role in reducing emissions: hydrogen power for on-farm machinery, cover crops, biologicals, livestock heat stress management, and conversion to hybrid and electric fishing vehicles. Furthermore, the science around emissions has advanced with continued academic research and the increased availability of technologies such as satellite imagery of croplands, all of which has improved our understanding of cost position, emissions reduction, and the implementation potential of measures.

To understand how the sector can achieve a 1.5° pathway, we developed a marginal abatement cost curve (MACC) to assess each measure's potential and average cost to abate one metric ton of CO_2e for global on-farm emissions (Exhibit 7).[55]

> **While many strategies have benefits in addition to reducing emissions and can be implemented at little to no cost to the farmer, economics remains a key barrier to at-scale adoption.**

Exhibit 6

Twenty-eight measures can support on-farm decarbonization in line with a 1.5˚ pathway, with most of the mitigation coming from the top 15.

■ Animal protein ■ Crops ■ Rice ■ Energy

Utilize advanced feed additives for livestock

~350 metric megatons of CO$_2$ equivalent (MtCO$_2$e), at cost of ~$99/tCO$_2$e

Apply nitrogen inhibitors and urease inhibitors on pasture

~214 MtCO$_2$e, at cost of ~$35/tCO$_2$e

Electrify agricultural machinery with renewable-energy sources

~167 MtCO$_2$e, at cost savings of ~$72/tCO$_2$e

Reduce overapplication of fertilizer on fields

~131 MtCO$_2$e, at cost savings of ~$146/tCO$_2$e

~58 MtCO$_2$e additional due production reduction

Apply nitrogen inhibitors and urease inhibitors on crop fields

~126 MtCO$_2$e, at cost savings of ~$37/tCO$_2$e

Improve animal health monitoring and illness prevention

~112 MtCO$_2$e, at zero cost

Employ partial straw removal in rice paddies

~112 MtCO$_2$e, at cost savings of ~$23/tCO$_2$e

Direct-seed rice

~104 MtCO$_2$e, at cost savings of ~$159/tCO$_2$e

Improve rice paddy water management

~97 MtCO$_2$e, at cost savings of ~$59/tCO$_2$e

Employ low- or no-till practices on crops

~91 MtCO$_2$e, at cost of ~$123/tCO$_2$e

~218 MtCO$_2$e additional due to sequestration

Convert from flood to drip or sprinkler irrigation

~85 MtCO$_2$e, at cost of ~$116/tCO$_2$e

Employ greenhouse gas–focused breeding and genetic selection in livestock production

~81 MtCO$_2$e, at zero cost

Expand use of large-scale anaerobic digestors

~80 MtCO$_2$e, at cost of ~$311/tCO$_2$e

Convert to use of enhanced-efficiency fertilizers

~73 MtCO$_2$e, at cost of ~$904/tCO$_2$e

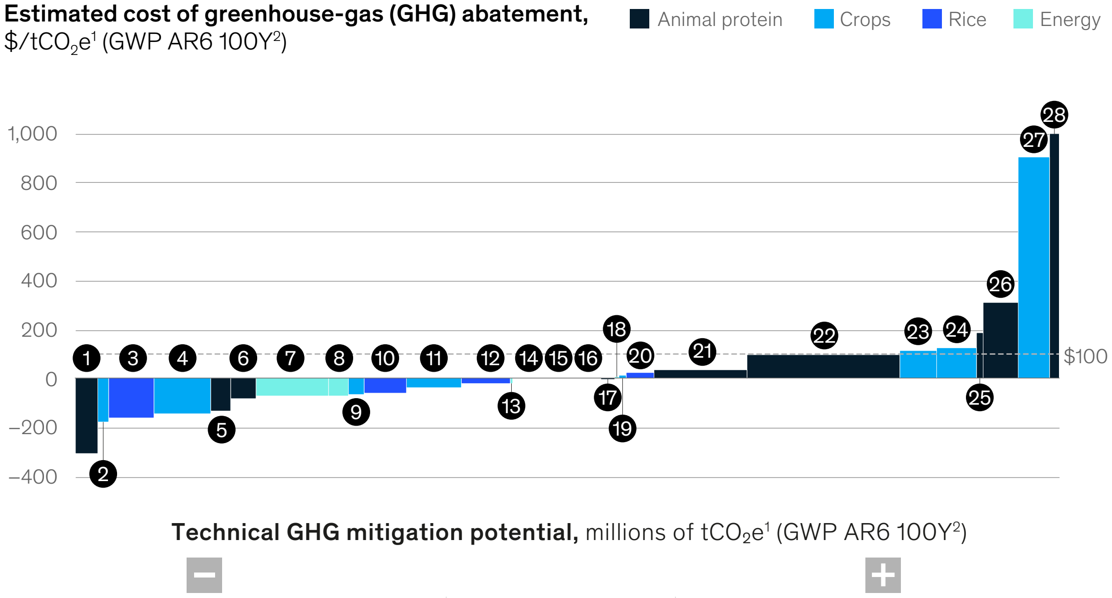
Apply sulfate fertilizer on rice paddies

~63 MtCO$_2$e, at cost of ~$22/tCO$_2$e

Exhibit 7a

A marginal abatement cost curve (MACC) shows the relative costs of identified decarbonization measures.

Estimated cost of greenhouse-gas (GHG) abatement, $\$/\text{tCO}_2\text{e}$[1] (GWP AR6 100Y[2])



1	Increase concentrate-to-forage ratio	**−306**
2	Biologicals	**−177**
3	Direct seeding of rice	**−159**
4	Reduced overapplication of fertilizer	**−146**
5	Expanded adoption of technologies that increase livestock production	**−135**
6	Heat stress management	**−84**
7	Electrification of on-farm machinery	**−72**
8	Hydrogen power for on-farm machinery	**−71**
9	Variable-rate fertilization	**−64**
10	Improved rice paddy water management	**−59**
11	Nitrogen inhibitors on crop fields	**−37**
12	Improved rice straw management	**−23**
13	Improved fuel efficiency in fishing vehicles	**−22**
14	Biochar as a fertilizer	**0**
15	Improved animal health and disease treatments	**0**
16	GHG-focused breeding and genetic selection	**0**
17	Feed grain processing for digestibility	**1**
18	Conversion to hybrid and electric fishing vessels	**5**
19	Incorporation of cover crops	**10**
20	Sulfate fertilization of rice	**22**
21	Nitrogen inhibitors on pastures	**34**
22	Advanced feed additives	**99**
23	Conversion from flood to drip or sprinkler irrigation	**116**
24	Low- or no-tillage	**123**
25	Shift to a higher-fat diet	**188**
26	Large-scale anaerobic manure digestion	**311**
27	Enhanced efficiency fertilizers	**904**
28	Small-scale anaerobic manure digestion	**1,000+**

Note: The width of each bar on the horizontal axis reflects GHG mitigation potential for each lever; the vertical axis displays the average abatement cost ($\$/\text{tCO}_2\text{e}$) for each lever; the total abatement potential is less than the full width of the marginal abatement cost curve (MACC) due to the potential for interaction between some levers.

[1] Metric tons of carbon dioxide equivalent.

[2] Global warming potential, as outlined in the 100-year scenario of the Intergovernmental Panel on Climate Change's *Sixth Assessment Report*.

Exhibit 7b

A marginal abatement cost curve (MACC) shows the relative costs of identified decarbonization measures. (continued)

	Animal protein	Crops	Rice	Energy
GHG emissions, % reduction (vs 2050 "do nothing" emissions)	–23	–36	–59	–15
GHG emissions, amount of reduction in metric gigatons (Gt) of CO_2e (vs 2050 "do nothing" emissions)	1.1	0.6	0.4	0.2

The MACC excludes some measures within the agriculture value chain that can reduce upstream impact or land use because they are not directly tied to on-farm emissions.[56] For example, the opportunity associated with green and blue hydrogen for fertilizer production or on-farm land-use practices such as agroforestry cannot be overstated (see sidebar "Fertilizer and pesticide production").

At-scale adoption of decarbonization measures is not straightforward, and many barriers exist. The economics of a given change remains at the forefront for farmers, but other external factors—including access to financing, grower education, and regulations and incentives, such as from carbon markets—will also influence adoption. For example, approximately 39 percent of surveyed farmers cited a lack of understanding as a primary reason for not participating in a carbon program.[57]

Fertilizer and pesticide production

The production phase of fertilizer is responsible for an estimated 39 percent of the product's emissions (roughly 425 metric megatons of CO_2 equivalent [$MtCO_2e$])[1] and nearly all greenhouse-gas (GHG) emissions associated with pesticides (roughly 135 $MtCO_2e$).[2] Thus, there is impetus to move away from the current fossil fuel–driven production processes, and blue and green hydrogen are emerging as potential solutions. In blue-hydrogen projects, traditional fossil-fuel inputs are still used, but 50 to 90 percent of the carbon is captured and stored, depending on implementation. By contrast, green hydrogen uses renewables to power electrolysis, creating almost zero emissions. The hydrogen created in these systems can then be used to create clean ammonia for use in nitrogen fertilizers. Estimates suggest that nearly 26 metric megatons (Mt) of sustainable ammonia will be produced per year by 2030—equivalent to 16 percent of the total global ammonia market excluding China—roughly six Mt of which is expected to be applied in green fertilizers.[3] Falling renewables costs, increased electrolysis capacity, supportive regulation, and acceleration of strategic industry alliances can make low-carbon hydrogen cost-competitive compared with fossil fuel–reliant gray hydrogen before 2030 and can further expedite adoption of these technologies.

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[1] Alicia Ledo, Stefano Menegat, and Reyes Tirado, "Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture," *Scientific Reports*, August 2022, Volume 12, Number 14490.

[2] E. Audsley et al., "Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use," Cranfield University, August 2009.

[3] Bernd Heid, Alma Sator, Maurits Waardenburg, and Markus Wilthaner, "Five charts on hydrogen's role in a net-zero future," McKinsey, October 25, 2022.

Changes that address climate change interact with other goals

A number of practices have planetary and humanitarian benefits for the four goals of agriculture (nature positivity, emissions reduction, productivity and food security, and inclusivity and health).[58]

For example, among other benefits, regenerative farming practices such as low- or no-tillage and cover cropping can improve nitrogen and phosphorous flows by increasing soil organic matter and reducing the need for synthetic fertilizers. Variable-rate fertilization can promote a healthy biosphere by limiting overapplication of fertilizer and limiting eutrophication—the accumulation of nutrients in lakes or other bodies of water—in nearby ecosystems caused by runoff. And anaerobic digesters can support economic growth in rural communities during construction and maintenance and provide farmers with new revenue streams for energy sold.

But these practices can also have negative trade-offs that stakeholders should consider as they work toward these changes. For example, feed processing for livestock protein may not be financially viable for small-scale farmers and may come at the expense of inclusion and financial security. Shifting toward certain processed alternative proteins may have health impacts that are not yet fully understood, and reducing fertilizer use or shifting toward biologicals could affect crop yield and subsequent food security if not implemented properly. All practices should be recommended in specific, regional, and population-dependent contexts and are not meant to be applied in a one-size-fits-all solution.

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Achieving progress at scale

As the risks of climate change grow, food systems will be tasked with creating more products with fewer inputs in increasingly difficult conditions. By 2050, the world's population is expected to reach ten billion, while the likelihood of a 15 percent shock to grain production is estimated to double by 2030 as a result of climate change.[59] As the MACC shows, established and innovative solutions exist for agriculture to achieve a 1.5° pathway, but meaningful barriers currently limit uptake of these solutions. This presents a unique opportunity for businesses and investors to accelerate adoption and capture additional value. Key barriers to adoption and associated opportunities include novel financing to provide adequate incentives for farmers, ecosystem collaboration and value chain traceability, and bending the cost curve through innovation.

Novel financing to provide adequate incentives for farmers

The considerable number of farmers and stakeholders across the value chain creates challenges for addressing agriculture's planetary impact at scale. Roughly one in four members of the global workforce is employed by the agriculture industry.[60] However, farming is by no means a centralized industry: more than 80 percent of farms are smaller than two hectares, about the size of three soccer fields, and these small farms account for 30 to 34 percent of the planet's food supply.[61] As a result, many farmers today are focused on near-term financial performance and may not have adequate incentives to adopt sustainable practices and technologies. For example, in the United States, only 14.5 cents per dollar spent on food went to farmers in 2021, the lowest amount in three decades, and 50 percent of farmers cite low ROI as a top reason for not participating in carbon programs.[62]

Financial incentives for farmers to adopt sustainable technologies are emerging, such as carbon and biodiversity markets, green premiums on consumer food products, and specific project incentives, such as California's FARMER program, which funds new electric equipment. Although these mechanisms can provide value to farmers, they remain nascent. For example, as the MACC illustrates, nearly all production-side abatement opportunities could be financially viable at an average carbon price of $150 per metric ton. However, agricultural carbon credits account for just over 1 percent of credits issued.[63] If this financial burden is left to the farmer, adoption is likely to be low. Lack of access to capital also limits farmers' adoption of interventions with high investment needs, especially on small farms, and longer time frames of potential payoffs further limit uptake for farmers late in their careers. Thus, ecosystem players will need to develop novel financing approaches to support uptake. If implemented with care, these solutions can continue to support the livelihoods of farmers large and small while unlocking additional revenue streams.

Ecosystem collaboration and value chain traceability

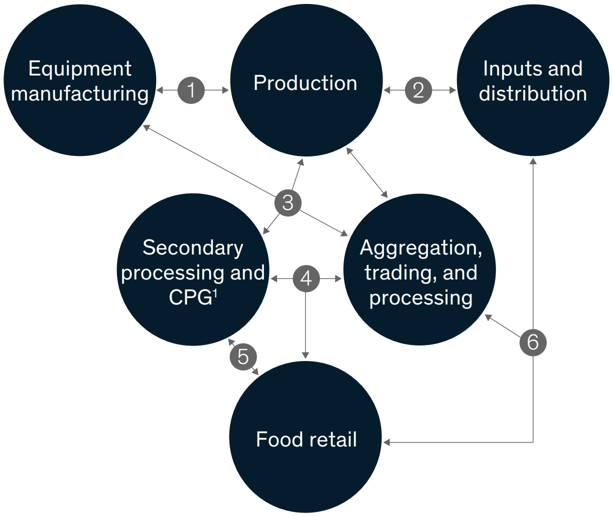
Achieving at-scale adoption of decarbonization solutions and capturing the associated value will require ecosystem players to collaborate in new ways (Exhibit 8). In many cases, collaborations can involve partners from multiple stages of the value chain as well as external stakeholders, such as investors. For example, adequate practice verification will be necessary to monetize practice adoption and create novel consumer-facing products downstream. Purchasers must be able to track product traits, such as crops farmed using regenerative practices, in order to create consumer-facing products and generate green premiums. Similarly, retailers must be able to adequately bring this transparency to consumers. Creating this transparency will require collaboration across the value chain but can support standardized consumer labeling and foster trust in carbon and biodiversity, all of which can help create additional value.

Bending the cost curve through innovation

While most opportunities are viable at an average carbon price of $150 per metric ton, practices are unlikely to be adopted at scale until costs decrease, especially in less developed regions and on smaller farms. Public investment in R&D today is increasing but not uniformly across geographies. For example, while inflation-adjusted public investment is decreasing in the United States, it is increasing in many other regions with large agricultural economies, such as China, the European Union, and Brazil.[64] Public and private investors thus have a key role to play in accelerating progress toward a more sustainable future. Private investment in agtech, including sustainable agriculture,

Exhibit 8

Ecosystem players will need to work together to address decarbonization issues and capture associated value.



Collaboration across the value chain will be required to ensure sufficient value flows to producers; other stakeholders may be involved (eg, investors and insurance)

1. **Create novel financing mechanisms** to support adoption of capital-intensive next-generation equipment (eg, electric vehicles and equipment for regenerative agriculture, anaerobic digestion, or drip irrigation)
2. **Launch price-competitive alternative products and services** (eg, biologicals or carbon programs) as well as education to drive adoption among producers
3. **Drive adoption of improved tracking and tracing** solutions to validate farmer practices, track "sustainability traits," and reduce food loss with supply and demand matching
4. **Scale waste-to-value streams** to address food loss and food waste emissions (eg, waste for biofuel production)
5. **Roll out—and educate consumers about—trustable products and labels** to capture consumer premiums for sustainable production
6. **Improve crop genetics** to reduce perishability and value chain loss (eg, due to bruising)

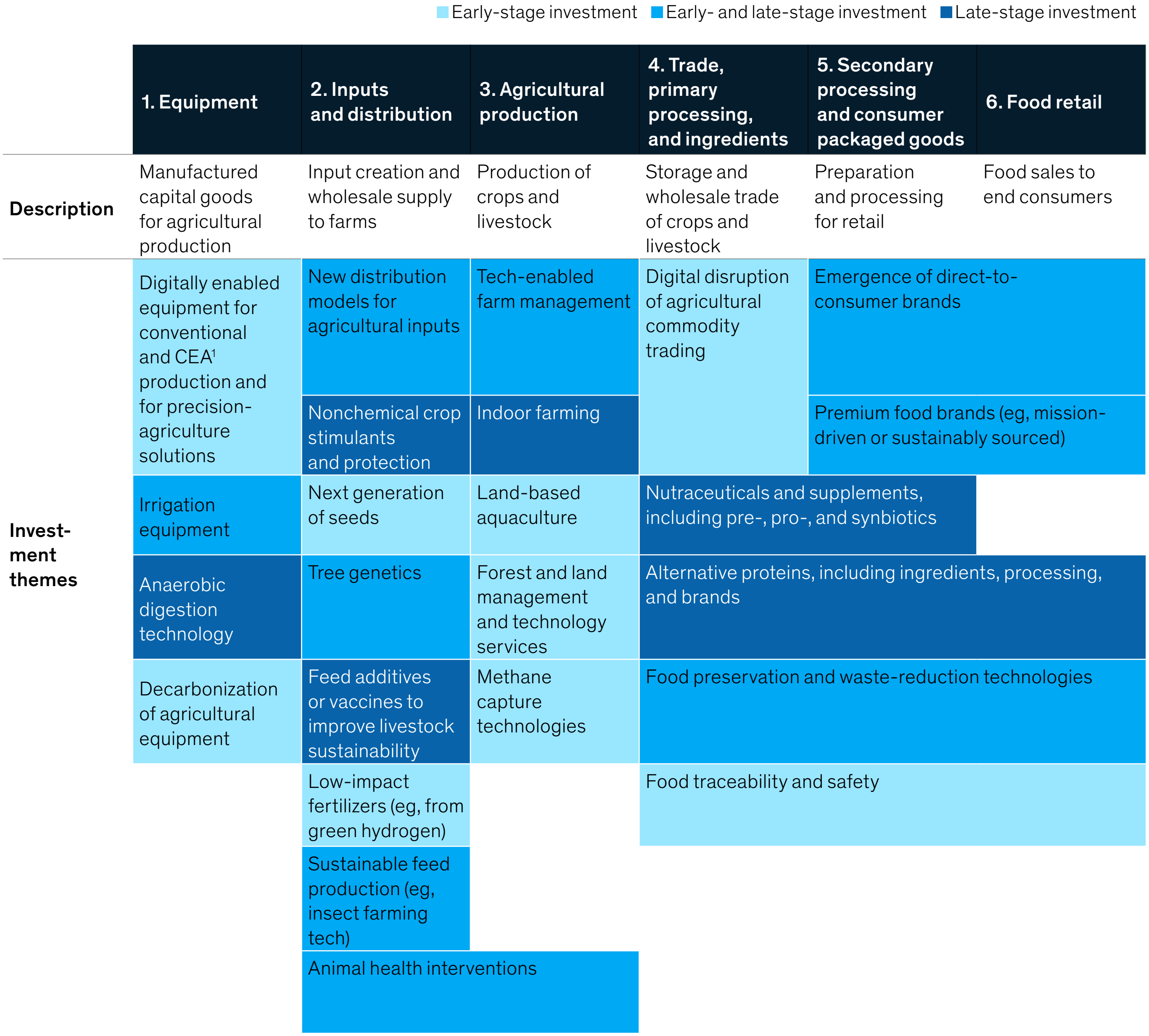
[1] Consumer packaged goods.

has been growing rapidly, with nearly 20 times more capital in new ventures in 2021 than in 2012. And although the total amount of investment saw a meaningful decrease between 2021 and 2022, there are still reasons for optimism. In fact, the second quarter of 2022 alone saw more funding in agtech than any quarter prior to the fourth quarter of 2020.[65]

Continued and accelerated investment will be required to bend the cost curve for existing solutions and support the development and adoption of new solutions. With this in mind, we developed a set of 24 sustainable-investment themes targeted at the agriculture sector (Table). Themes are divided across the value chain based on investment stages. Notably, some opportunities are seeing both early- and late-stage investments. For example, many farm management technologies are seeing late-stage investments, while new solutions leveraging satellite imagery are in a relatively early stage of investing.

Barriers to achieving the adoption necessary to a reach a 1.5° pathway are meaningful. Progress is being made, but it will need to accelerate to provide the motivation farmers and consumers need to act. Investors and industry players across the value chain have a unique opportunity to capture value while creating this motivation.

Table. A number of actionable investment themes can help players capture the value associated with decarbonization across the agricultural value chain.



░ Early-stage investment ▒ Early- and late-stage investment ▓ Late-stage investment

	1. Equipment	**2. Inputs and distribution**	**3. Agricultural production**	**4. Trade, primary processing, and ingredients**	**5. Secondary processing and consumer packaged goods**	**6. Food retail**
Description	Manufactured capital goods for agricultural production	Input creation and wholesale supply to farms	Production of crops and livestock	Storage and wholesale trade of crops and livestock	Preparation and processing for retail	Food sales to end consumers
Invest-ment themes	Digitally enabled equipment for conventional and CEA[1] production and for precision-agriculture solutions	New distribution models for agricultural inputs	Tech-enabled farm management	Digital disruption of agricultural commodity trading	Emergence of direct-to-consumer brands	
		Nonchemical crop stimulants and protection	Indoor farming		Premium food brands (eg, mission-driven or sustainably sourced)	
	Irrigation equipment	Next generation of seeds	Land-based aquaculture	Nutraceuticals and supplements, including pre-, pro-, and synbiotics		
	Anaerobic digestion technology	Tree genetics	Forest and land management and technology services	Alternative proteins, including ingredients, processing, and brands		
	Decarbonization of agricultural equipment	Feed additives or vaccines to improve livestock sustainability	Methane capture technologies	Food preservation and waste-reduction technologies		
		Low-impact fertilizers (eg, from green hydrogen)		Food traceability and safety		
		Sustainable feed production (eg, insect farming tech)				
		Animal health interventions				

[1] Controlled-environment agriculture.

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Conclusion

Although the path to achieving 1.5°C will not be straightforward, it can create real business value for farmers and players throughout the value chain, with additional environmental benefits beyond reducing climate change. Action will be required beyond the farm, but there is a real opportunity to drive on-farm decarbonization while capturing business value. A more sustainable future for agriculture that feeds a growing planet while maintaining the livelihoods of farmers is feasible. And industry players, policy makers, and investors can accelerate the path to the future while enabling their own growth.

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Appendix

Calculating a baseline for agriculture emissions

The marginal abatement cost curve (MACC) is tied to global values and projections of on-farm emissions. As such, it does not use other forms of emissions as its reference point, and it does not include the measures that primarily affect these other forms of emissions, such as carbon sequestration or reductions in production of inputs (feed, feedstock, and so on). Many measures have additional potential to reduce emissions beyond on-farm emissions; we highlighted this potential but did not include these measures in the MACC to ensure an accurate representation of reductions against the on-farm baseline. In addition, many measures have cobenefits to support goals beyond decarbonization (Table A1). And some measures are tied to yield uplift, which we have accounted for in both the costs and the greenhouse-gas (GHG) impact associated with the production changes of yield uplift.

The baseline created for agriculture emissions and used in the creation of the MACC was based on the Agriculture Emissions Database developed by the Food and Agriculture Organization of the United Nations (FAO),[66] with several minor adjustments:

- Nitrous oxide and methane emissions were adapted to reflect the global warming potential (GWP100) values from the *Sixth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC).

- Because the FAO does not provide forward-looking estimates for "energy use in agriculture," regional values for 2030 and 2050 were estimated based on the FAO's future-acreage projections.

- Similarly, the value for "cultivation of organic soils" was held constant from 2020 onward because the FAO does not provide forward-looking projections for this value and recently reported data show limited growth.

The baseline was developed with the FAO's baseline of agricultural emissions based on the following definitions:

Land-use change refers to emissions associated with land conversion for agriculture. The most common source of these emissions is deforestation. Because of uncertainty about the relative potential of restoration and conservation efforts versus future land conversion, our research assumed zero growth in this category from 2030 to 2050.

Enteric fermentation refers to methane emitted during the digestion process by ruminants, such as cattle, sheep, and goats. Ruminants have a rumen, a second stomach that allows them to consume and digest cellulose plants and grains that monogastric animals, such as humans, cannot. When ruminants consume carbohydrates, methanogens in the rumen decompose them into methane in a process called methanogenesis. This methane is ultimately released into the atmosphere and is considered a main source of GHG emissions. The majority of these emissions come from beef and dairy cattle.

Energy use in agriculture refers to on-farm energy use related to fuel combustion and electricity generation for agricultural activities, including fisheries.

Manure left on pasture refers to emissions, primarily nitrogen runoff, from animal waste left on grazing lands.

Synthetic fertilizers refers to nitrous oxide emissions from excess use of nitrogen-based fertilizers in croplands. Although these on-farm emissions are significant, they account for only about 59 percent of the GHG emissions associated with a metric ton of synthetic fertilizer.[67] The remaining emissions occur upstream, primarily during transportation (about 3 percent) and ammonia synthesis in production (about 39 percent).[68]

Rice cultivation refers to the methane emissions that result from rice paddies. These flooded fields block oxygen from penetrating the soil, forcing organic material to decompose anaerobically and creating methane emissions. In addition, the rice straw left on the field after harvesting is typically cleared by burning, which results in significant CO_2 emissions.

Manure management refers to emissions during the storage and processing of manure. Methane can be emitted from its anaerobic decomposition, and nitrous oxide can be emitted during storage and processing, where it is released as ammonia and later transformed into nitrous oxide in indirect emissions.

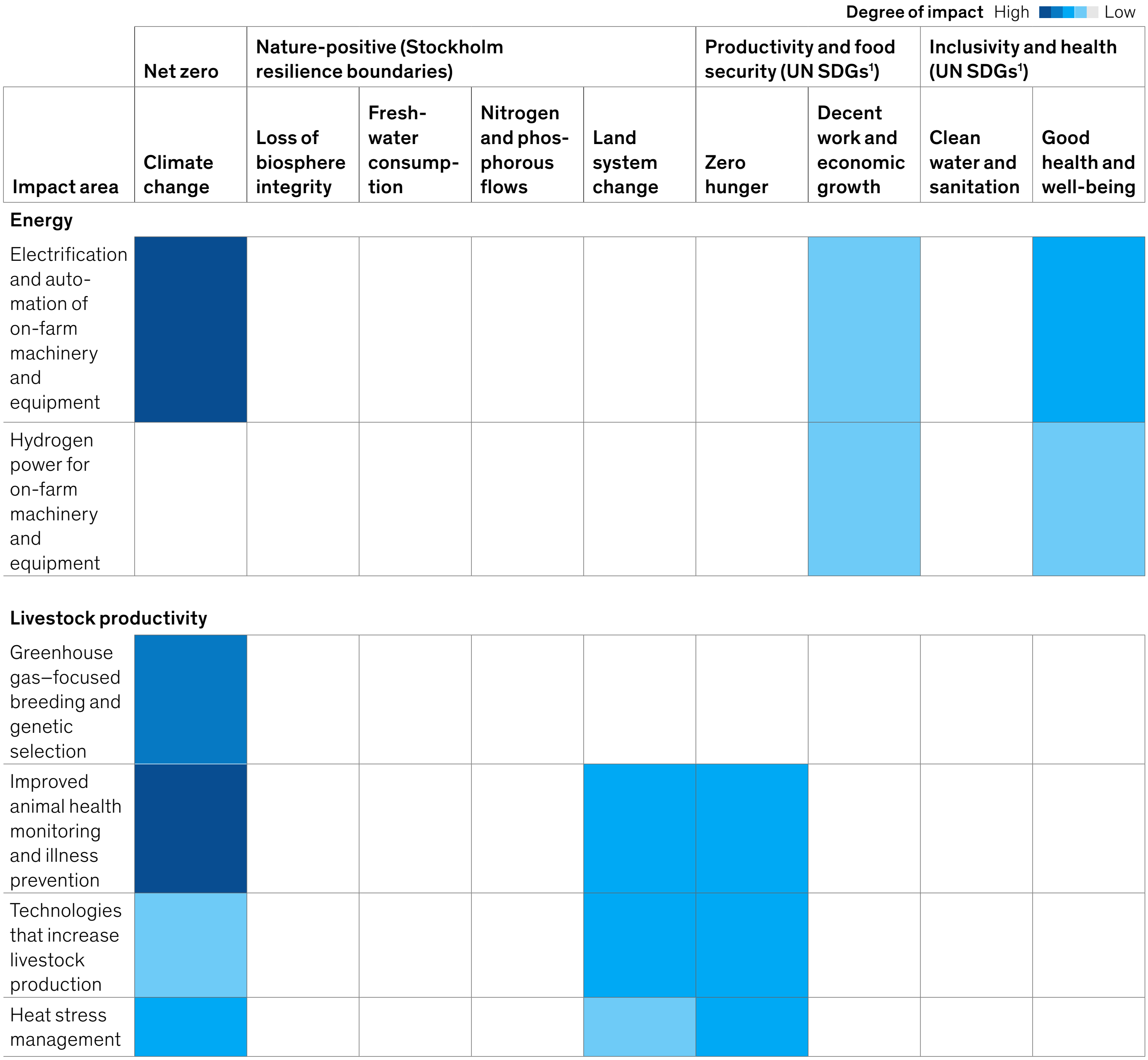
Table A1. Many levers have cobenefits to support goals beyond decarbonization.

Degree of impact High █▓▒░□ Low

	Net zero	**Nature-positive (Stockholm resilience boundaries)**				**Productivity and food security (UN SDGs[1])**		**Inclusivity and health (UN SDGs[1])**	
Impact area	**Climate change**	**Loss of biosphere integrity**	**Freshwater consumption**	**Nitrogen and phosphorous flows**	**Land system change**	**Zero hunger**	**Decent work and economic growth**	**Clean water and sanitation**	**Good health and well-being**
Rice									
Dry direct seeding	▓		▓					▓	
Improved rice paddy water management	▓		▓					▓	
Sulfate fertilization of rice	█								
Improved rice straw management	▓						▒		

Degree of impact High █▓▒░▫ Low

	Net zero	Nature-positive (Stockholm resilience boundaries)				Productivity and food security (UN SDGs[1])		Inclusivity and health (UN SDGs[1])	
Impact area	**Climate change**	**Loss of biosphere integrity**	**Freshwater consumption**	**Nitrogen and phosphorous flows**	**Land system change**	**Zero hunger**	**Decent work and economic growth**	**Clean water and sanitation**	**Good health and well-being**
Fertilizer efficiency									
Reduced over-application of fertilizer	▒	▒		█				▒	░
Enhanced-efficiency fertilizers	░	▒		▒				░	░
Variable-rate fertilization	░	░		▒	▒	░		░	░
Nitrogen and urease inhibitors on crop fields	█	▓		▒	░	▫		░	░
Biochar as a soil amendment	▫	▫		▫			░		▫
Other crop production management									
Low- or no-tillage	▓	▫	▒	░				▫	▫
Conversion from flood to drip or sprinkler irrigation	▒		█	░				█	
Incorporation of cover crops	▫	▫	▫	░	▫	▫		░	
Biologicals (including biopesticides and biostimulants)	▫	▫		▫			░		▫



Degree of impact High █▓▒░□ Low

	Net zero	Nature-positive (Stockholm resilience boundaries)				Productivity and food security (UN SDGs[1])		Inclusivity and health (UN SDGs[1])	
Impact area	**Climate change**	**Loss of biosphere integrity**	**Freshwater consumption**	**Nitrogen and phosphorous flows**	**Land system change**	**Zero hunger**	**Decent work and economic growth**	**Clean water and sanitation**	**Good health and well-being**
Energy									
Electrification and automation of on-farm machinery and equipment	█						░		▒
Hydrogen power for on-farm machinery and equipment							░		░
Livestock productivity									
Greenhouse gas–focused breeding and genetic selection	▓								
Improved animal health monitoring and illness prevention	█				▒	▒			
Technologies that increase livestock production	░				▒	▒			
Heat stress management	▒				░	▒			

Degree of impact High ■▩▦▤□ Low

	Net zero	Nature-positive (Stockholm resilience boundaries)				Productivity and food security (UN SDGs[1])		Inclusivity and health (UN SDGs[1])	
Impact area	**Climate change**	**Loss of biosphere integrity**	**Freshwater consumption**	**Nitrogen and phosphorous flows**	**Land system change**	**Zero hunger**	**Decent work and economic growth**	**Clean water and sanitation**	**Good health and well-being**
Livestock feeding practices									
Feed grain processing for digestibility (steam-flaking)	▤				▤	▤			
Shift to higher-fat diet	▦								
Decrease forage-to-concentrate ratio	▦								
Advanced feed additives	■			□	▦		□		
Manure management									
Nitrogen inhibitors and urease inhibitors on pasture	■			▦				▤	▤
Large-scale anaerobic manure digestion	▩	▦		▦			▦	▦	▤
Small-scale anaerobic manure digestion	▤	▤		▦			▦	▦	□
Aquaculture and fisheries									
Improved fuel efficiency in fishing vessels	□								
Conversion to hybrid and electric fishing vehicles	□						□	▤	

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[1] United Nations Sustainable Development Goals.

Calculating the MACC levers' emission-reduction potential and costs

The emissions abatement and cost for each mitigation lever were calculated from the bottom up, using data on applicability, adoption, abatement potential, yield impacts, and related costs from sources including academic research, interviews with content experts, and industry reports. The capital costs for relevant levers were calculated using a weighted average cost of capital of 5 percent, and total cost was calculated using the levelized cost of production, which calculates the annual unit revenue needed to break even against costs. In addition, several levers were considered for the MACC but were ultimately excluded because of relatively low anticipated impact and overlap with other levers (Table A2).

Table A2. Several levers were considered for inclusion in the marginal abatement cost curve but were ultimately excluded.

Category		Potential measure
Animal proteins	**Manure management**	Improved housing and bedding practices
	Aquaculture and fisheries	Shifted fishing strategies (eg, from trawl to seine)
		Regeneration of fish stocks
		Integrative multitrophic aquaculture
		Increased penetration of aquaponics
		Switch to land-based fish farming
	Livestock feed composition	Alternative protein feeds (eg, insect feed)
		Improved forage quality
		Right-size feeding volumes
	Other livestock systems management	Optimization of slaughter age
		Assisted reproductive technologies
Crops	**Other crop production management**	Improved equipment maintenance
		Integrated pest management
		Expanded acreage under irrigation
		Crop breeding for improved productivity and sequestration
		Sale of biomass to biochar production
		Decarbonization of pesticide production and use
		Agroforestry
		Controlled environment agriculture
	Fertilizer management	Low-carbon fertilizer manufacturing (eg, green hydrogen–based production)
		Microbial fertilizer or biofertilizer
		Digestate as soil amendment

Category		Potential measure
Food systems	**Waste reduction**	Shelf-life tracking and management
		Software tracking for produce
Rice	**Selection**	Optimal rice varietal selection
Energy	**Energy efficiency**	Replace HPS lighting with LEDs in greenhouses
		Penetration of lightweight equipment
		Increased heating efficiency and management

The following detailed lever deep dives include description, discussion, calculation methodology, and sources.

1 Direct seeding of rice

Reduced methane emissions due to less flooding required when using a direct seeding technique rather than transferring seedlings into flooded paddies

634 **Baseline applicable emissions,** million tCO$_2$e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

40 **Incremental lever implementation,** % [B]

Source: Mathijs Harmsen, "Non-CO$_2$ greenhouse gas mitigation in the 21st century," Utrecht University, June 21, 2019

40 **Greenhouse-gas reduction factor,**[2] % CO$_2$e [C]

Source: A. Bhatia et al., "Dry direct-seeding of rice for mitigating greenhouse gas emission: Field experimentation and simulation," *Paddy and Water Environment*, December 2012, Volume 11; Chris van Kessel et al., "Modeling methane and nitrous oxide emissions from direct-seeded rice systems," *Journal of Geophysical Research: Biogeosciences*, October 2015, Volume 120; Debashis Chakraborty et al., "A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production," *Scientific Reports*, August 2017, Volume 7, Number 9342; Kehui Cui et al., "Dry direct-seeded rice as an alternative to transplanted-flooded rice in Central China," *Agronomy for Sustainable Development*, July 2014, Volume 35; Priyanka Gautam et al., "Management of direct seeded rice for enhanced resource - use efficiency," *Plant Knowledge Journal*, 2013, Volume 2, Number 3; R. Kartikawati et al., "The opportunity of direct seeding to mitigate greenhouse gas emission from paddy rice field," *IOP Conference Series: Earth and Environmental Science*, 2019, Volume 393; Virender Kumar and Jagdish K. Ladha, "Chapter six - Direct seeding of rice: Recent developments and future research needs," *Advances in Agronomy*, 2011, Volume 111

104 **Emission-reduction potential,** million tCO$_2$e[1] [A × B × C][3]

(159) **Lever implementation cost savings,** \$/tCO$_2$e[1]

Source: Minh D Ngo et al., *The current adoption of dry-direct seeding rice (DDSR) in Thailand and lessons learned for Mekong River Delta of Vietnam*, CGIAR CCFAS (Climate Change, Agriculture and Food Security) working paper, Number 273, June 2019

2 Improved rice paddy water management

Reduced methane emissions due to less flooding required when using improved water management

634 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

35 **Incremental lever implementation,** % [B]

Source: Wina H.J. Crijns-Graus, Mirjam Harmelink, and Chris Hendriks, “Marginal GHG-abatement curves for agriculture,” Ecofys, April 2004; Mathijs Harmsen, “Non-CO_2 greenhouse gas mitigation in the 21st century,” Utrecht University, June 21, 2019

44 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Daniela Carrijo, Bruce Linquist, and Henry Perry, “Single midseason drainage events decrease global warming potential without sacrificing grain yield in flooded rice systems,” *Field Crops Research*, February 2022, Volume 276, Number 108312; Nimlesh Balaine et al., “Water management to mitigate the global warming potential of rice systems: A global meta-analysis,” *Field Crops Research*, March 2019, Volume 234; Salvatore Calabrese, Rodolfo Souza, and Jun Yin, “Optimal drainage timing for mitigating methane emissions from rice paddy fields,” *Geoderma*, July 2021, Volume 394, Number 114986; X.Z. Du et al., “Effects of irrigation regime and rice variety on greenhouse gas emissions and grain yields from paddy fields in central China,” *Agricultural Water Management*, May 2021, Volume 250, Number 106830

97 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

(59) **Lever implementation cost savings,** $/$tCO_2e$[1]

Source: Bas A.M. Bouman et al., “Adoption and economics of alternate wetting and drying water management for irrigated lowland rice,” *Field Crops Research*, January 2015, Volume 170

3 Sulfate fertilization of rice

Sulfate fertilizers or sulfate amendments reduce emissions from rice production by affecting methane-producing organisms

634 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

25 **Incremental lever implementation,** % [B]

Source: IHS Markit

40 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Arti Bhatia et al., “Plummeting global warming potential by chemicals interventions in irrigated rice: A lab to field assessment,” *Agriculture, Ecosystems & Environment*, October 2021, Volume 319, Number 107545; Maria Arlene Adviento-Borbe et al., “Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis,” *Field Crops Research*, August 2012, Volume 135

63 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

22 **Lever implementation cost,** $/$tCO_2e$[1]

Source: International Fertilizer Association; SunSirs; World Bank

Note: Operating expenditure costs are based on the difference in price for ammonium sulfate (~$200/metric ton [t] using 21% nitrogen [N] in the product = ~$952/t N basis) verses urea (~$300/t using 46% N in product = $652/t); thus, an extra $300/t is calculated for an application of 119 kg N ha–1 per rice crop.

4 Improved rice straw management

Removing rice straw from fields prevents the breakdown of the organic matter and subsequently reduces methane release

634 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

40 **Incremental lever implementation,** % [B]

Source: Mathijs Harmsen, "Non-CO_2 greenhouse gas mitigation in the 21st century," Utrecht University, June 21, 2019

44 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Ma. Carmelita Alberto et al., "How does burning of rice straw affect CH_4 and N_2O emissions? A comparative experiment of different on-field straw management practices," *Agriculture, Ecosystems & Environment*, February 2017, Volume 239; Anlei Chen et al., "Mitigating effects of ex situ application of rice straw on CH_4 and N_2O emissions from paddy-upland coexisting system," *Scientific Reports*, November 2016, Volume 6, Number 37402

112 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

(23) **Lever implementation cost savings,** $/$tCO_2e$[1]

Source: Constancio A. Asis et al., "Cost-effectiveness analysis of farmers' rice straw management practices considering CH_4 and N_2O emissions," *Journal of Environmental Management*, December 2016, Volume 183; Constancio A. Asis et al., "Economic analysis of rice straw management alternatives and understanding farmers' choices," *Cost-Benefit Studies of Natural Resource Management in Southeast Asia*, 2015

5 Reduced overapplication of fertilizer

Limiting application of nitrogen to exact levels reduces nitrogen lost to the atmosphere via nitrogen emissions

773 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

100 **Incremental lever implementation,** % [B]

Source: Mathijs Harmsen, "Non-CO_2 greenhouse gas mitigation in the 21st century," Utrecht University, June 21, 2019

58 **Additional emission-reduction potential from reductions in production,** million tCO_2e[1]

Source: Alicia Ledo, Stefano Menegat, and Reyes Tirado, "Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture," *Scientific Reports*, August 2022, Volume 12, Number 14490; assuming 3.8 kg emissions per kg of nitrogen, based on global production emissions; assuming proportional reduction in emissions is equivalent to reduction in fertilizer use

17 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: *Reducing emissions from fertilizer use*, International Fertilizer Association and SystemIQ, September 2022

131 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

(146) **Lever implementation cost savings,** $/$tCO_2e$[1]

Source: Alicia Ledo, Stefano Menegat, and Reyes Tirado, "Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture," *Scientific Reports*, August 2022, Volume 12, Number 14490; assuming 3.8 kg emissions per kg of nitrogen, based on global production emissions; assuming proportional reduction in emissions is equivalent to reduction in fertilizer use

6

Specialty fertilizers

Conversion from traditional synthetic fertilizers to enhanced-efficiency fertilizers (EEFs) to reduce nitrous oxide emissions

773 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

30 **Incremental lever implementation,** % [B]

Source: Expert interviews; McKinsey analysis

19 **Additional emission-reduction potential from reductions in production,** million tCO_2e[1]

Source: Alicia Ledo, Stefano Menegat, and Reyes Tirado, "Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture," *Scientific Reports*, August 2022, Volume 12, Number 14490; assuming 3.8 kg emissions per kg of nitrogen, based on global production emissions; assuming proportional reduction in emissions is equivalent to reduction in fertilizer use

35 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: McKinsey analysis

73 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

904 **Lever implementation cost,** \$/tCO_2e[1]

Source: Chad M. Hutchinson et al., "Controlled-release fertilizers for commercial potato production in Florida," University of Florida Institute of Food and Agricultural Sciences, updated November 2021; *Reducing emissions from fertilizer use*, International Fertilizer Association and SystemIQ, September 2022; conversion takes \$/hectare (ha) value and assumes 65% of cropland is treated with synthetic fertilizer for specific countries in scope, then applies the adoption rate for ha/tCO_2e[1] conversion

7

Variable rate fertilization

Applying different rates of nitrogen fertilizer to distinct areas of crops based on crop need rather than a flat rate across all fields, reducing excess fertilizer use and subsequent nitrogen emissions

773 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

30 **Incremental lever implementation,** % [B]

Source: McKinsey analysis

15 **Additional emission-reduction potential from reductions in production,** million tCO_2e[1]

Source: Alicia Ledo, Stefano Menegat, and Reyes Tirado, "Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture," *Scientific Reports*, August 2022, Volume 12, Number 14490; assuming 3.8 kg emissions per kg of nitrogen, based on global production emissions; assuming proportional reduction in emissions is equivalent to reduction in fertilizer use

15 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Median value of 15% gathered from Vera Eory et al., "Cost-effectiveness of greenhouse gas mitigation measures for agriculture," *OECD Food, Agriculture and Fisheries Papers*, August 2015; McKinsey analysis

35 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

(64) **Lever implementation cost savings,** \$/tCO_2e[1]

Source: J. Bates et al., "Sectoral emission reduction potentials and economic costs for climate change SERPEC-CC. Agriculture: Methane and nitrous oxide," Ecofys, October 2009 [quote of €20/hectare (ha) for "maintenance costs," which is \$27/ha using 2009 currency conversion rates; conversion takes \$/ha value and assumes 65% of cropland is treated with synthetic fertilizer for specific countries in scope, then applies the adoption rate for ha/tCO_2e[1] conversion]; Vera Eory et al., "Cost-effectiveness of greenhouse gas mitigation measures for agriculture," *OECD Food, Agriculture and Fisheries Papers*, August 2015

8 Nitrogen and urease inhibitors on crop fields

Nitrification inhibitors (NIs) help soil retain nitrogen, reducing leaching of nitrate and related emissions, and are often used in conjunction with urease inhibitors to limit ammonia runoff

987 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

50 **Incremental lever implementation,** % [B]

Source: McKinsey Global Farmers Survey

25 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Diego Abalos et al., "A review and meta-analysis of mitigation measures for nitrous oxide emissions from crop residues," *Science of the Total Environment*, July 2022, Volume 828, Number 154388

126 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

(37) **Lever implementation cost savings,** \$/tCO_2e[1]

Source: Jana E Compton et al., "How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input," *Global Change Biology*, March 2015, Volume 21, Number 3; assuming a weighted average basket of the 3 commodities, averaging to \$772/hectare (ha) of value given: corn (5.75 metric tons [t]/ha; \$138/t), soy (2.78 t/ha; \$330/t), and wheat (3.47 t/ha; \$178/t)

Note: When used with synthetic fertilizers or manure, NIs lead to 30–50% direct nitrous oxide (N_2O) reductions—however, this is highly variable and lower in grassland, and indirect N_2O emissions from increased ammonium (NH_4) can lead to a 15% increase in emissions, offsetting some impact. There is also a 9% yield increase impact on average, but this differs by crop (for more, see details in lever cobenefits section).

9 Biochar as a soil amendment

Biochar application to agricultural soil reduces nitrous oxide (N_2O) and methane (CH_4) emissions

773 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

5 **Incremental lever implementation,** % [B]

6 **Additional emission-reduction potential from reductions in production,** million tCO_2e[1]

Source: Alicia Ledo, Stefano Menegat, and Reyes Tirado, "Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture," *Scientific Reports*, August 2022, Volume 12, Number 14490; assuming 3.8 kg emissions per kg of nitrogen, based on global production emissions; assuming proportional reduction in emissions is equivalent to reduction in fertilizer use

2,000 **Additional emission-reduction potential from sequestration,** million tCO_2e[1]

Source: Alicia Ledo, Stefano Menegat, and Reyes Tirado, "Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture," *Scientific Reports*, August 2022, Volume 12, Number 14490; assuming 3.8 kg emissions per kg of nitrogen, based on global production emissions; assuming proportional reduction in emissions is equivalent to reduction in fertilizer use

31 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Ghulam Haider et al., "Mineral nitrogen captured in field-aged biochar is plant-available," *Scientific Reports,* August 2020, Volume 10, Number 13816; Nanthi Bolan et al., "How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar," *GCB Bioenergy*, November 2021, Volume 13, Number 11

11 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

0 **Lever implementation cost,** \$/tCO_2e[1]

Source: Ghulam Haider et al., "Mineral nitrogen captured in field-aged biochar is plant-available," *Scientific Reports*, August 2020, Volume 10, Number 13816; Nanthi Bolan et al., "How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar," *GCB Bioenergy*, November 2021, Volume 13, Number 11

Note: The Intergovernmental Panel on Climate Change (IPCC) projects 2030 capacity to be between 2 million metric tons (t) and 7 million t of CO_2e sequestered; 1.0 t of biochar sequesters ~2.35 t of CO_2, so this suggests that the biochar supply should be 0.85 million t to 3.0 million t. At an application rate of 10–50 t/hectare (ha), this ranges from 17,000–298,000 ha of applied cropland. With 1.4 billion ha of cropland across the globe, ~65% of which is treated with synthetic fertilizer, this is at most 0.03% of cropland. To 2050, the IPCC assumes a 27–35% CAGR in biochar; 2050 sequestration opportunity is thus 300–2,000 million t, and using the same assumptions, this ranges from 0.3–9.0% of cropland.

10 Low- or no-tillage

Decrease emissions from on-farm energy use via reduced fuel consumption (in tillage), and from reduced need for synthetic fertilizer application and the resulting denitrification emissions

887 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

40 **Incremental lever implementation,** % [B]

Source: McKinsey Nature Analytics

218 **Additional emission-reduction potential from reductions in production,** million tCO_2e[1]

Source: McKinsey Nature Analytics

27 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Robert Beach et al., "Structural change as a key component for agricultural non-CO_2 mitigation efforts," *Nature Communications*, March 2018, Volume 9, Number 1060

91 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

123 **Lever implementation cost,** $/$tCO_2e$[1]

Source: McKinsey Nature Analytics

11 Conversion from flood to drip or sprinkler irrigation

Conversion from flood irrigation to drip or sprinkler irrigation can reduce CO_2 emissions from irrigation energy use as well as nitrous oxide (N_2O) emissions from the denitrification of synthetic nitrogen

321 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

65 **Incremental lever implementation,** % [B]

Source: McKinsey Nature Analytics

42 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Jia Deng et al., "Changes in irrigation practices likely mitigate nitrous oxide emissions from California cropland," *Global Biogeochemical Cycles*, September 2018, Volume 32, Number 10; Mohsin Hafeez, Tamara M. Jackson, and Shahbaz Khan, "A comparative analysis of water application and energy consumption at the irrigated field level," *Agricultural Water Management*, October 2010, Volume 97, Number 10

85 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

116 **Lever implementation cost,** $/$tCO_2e$[1]

Source: McKinsey analysis

12 Incorporation of cover crops

Decrease in emissions due to reduced need for fertilizer when cover crops are used

773 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

15 **Incremental lever implementation,** % [B]

Source: McKinsey Nature Analytics

8 **Additional emission-reduction potential from reductions in production,** million tCO_2e[1]

Source: Rob Myers, Sami Tellatin, and Alan Weber, “Cover crop economics: Opportunities to improve your bottom line in row crops,” Sustainable Agriculture Research and Education (SARE), 2019; assuming 3.8 kg of emissions per kg of nitrogen (N) or a 1.75 kg decrease in emissions per kg of fertilizer

56 **Additional emission-reduction potential from sequestration,** million tCO_2e[1]

Source: Rob Myers, Sami Tellatin, and Alan Weber, “Cover crop economics: Opportunities to improve your bottom line in row crops,” Sustainable Agriculture Research and Education (SARE), 2019; assuming 3.8 kg of emissions per kg of nitrogen (N) or a 1.75 kg decrease in emissions per kg of fertilizer; McKinsey Nature Analytics

15 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: FAOSTAT; Rob Myers, Sami Tellatin, and Alan Weber, “Cover crop economics: Opportunities to improve your bottom line in row crops,” Sustainable Agriculture Research and Education (SARE), 2019

17 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

10 **Lever implementation cost,** $/$tCO_2e$[1]

Source: Sustainable Agriculture Research and Education (SARE) and Conservation Technology Information Center (CTIC) National Cover Crop Surveys, 2012–16; McKinsey analysis

13 Biologicals

Optimization of crop yields and plant health through application of natural products, such as microbes, insects, or plant extracts rather than fertilizer, thus reducing emissions associated with fertilizer use

773 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

15 **Incremental lever implementation,** % [B]

Source: McKinsey analysis

11 **Additional emission-reduction potential from reductions in fertilizer production,** million tCO_2e[1]

Source: Gil Gullickson, “Companies are flooding farmers with numerous biostimulant products,” Successful Farming, December 3, 2021; assuming 3.8 kg of emissions per kg of nitrogen (N) or a 1.75 kg decrease in emissions per kg of fertilizer

24 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Andrea Colantoni and Sara Rajabi Hamedani, “Plant biostimulants and mitigation of greenhouse gas emission in crop production,” Biostimulant.com, accessed January 9, 2023

24 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

(177) **Lever implementation cost savings,** $/$tCO_2e$[1]

Source: Gil Gullickson, “Companies are flooding farmers with numerous biostimulant products,” Successful Farming, December 3, 2021

Note: The price of biologicals is likely to increase as the market matures and proves efficacy.

14 Electrification of on-farm machinery and equipment

Decreased emissions from on-farm machinery due to replacing fossil fuel–burning internal-combustion engine (ICE) vehicles and machinery with battery electric vehicles (BEVs)

547 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

30 **Incremental lever implementation,** % [B]

Source: Vivid Economics, a McKinsey company; McKinsey Center for Future Mobility; McKinsey analysis

100 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

167 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

(72) **Lever implementation cost savings,** \$/tCO_2e[1]

Source: Vivid Economics, a McKinsey company; McKinsey Center for Future Mobility; McKinsey analysis

Note: BEVs release no emissions, assuming electricity is sourced from renewable energy. Example capital expenditure differences between BEVs and ICEs: \$13,564 (2025) and \$11,535 (2050), per a 50–99 horsepower tractor; example operating expenditure differences between BEVs and ICEs: \$4,943 (2025) and \$6,494 (2050), annually for a 50–99 horsepower tractor.

15 Hydrogen power for on-farm machinery and equipment

Decreased emissions from on-farm machinery due to replacing fossil fuel–burning internal-combustion engine (ICE) vehicles and machinery with fuel cell electric vehicles (FCEVs)

547 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

10 **Incremental lever implementation,** % [B]

Source: Vivid Economics, a McKinsey company; McKinsey analysis

100 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

46 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

(71) **Lever implementation cost savings,** \$/tCO_2e[1]

Source: Vivid Economics, a McKinsey company; McKinsey Center for Future Mobility; McKinsey analysis

Note: FCEVs release no emissions, assuming electricity is sourced from renewable energy. Example capital expenditure differences between FCEVs and ICEs: \$70,887 (2025) and \$23,756 (2050), per a 50–99 horsepower tractor; example operating expenditure differences between FCEVs and ICEs: \$2,581 (2025) and \$6,273 (2050), annually for a 50–99 horsepower tractor.

16 Improved animal health and disease treatments

Expanded use of animal health solutions could reduce livestock system emissions through improved productivity and reduced losses and mortality

4,599 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

30 **Incremental lever implementation,** % [B]

Source: *Study to model the impact of controlling endemic cattle diseases and conditions on national cattle productivity, agricultural performance and greenhouse gas emissions*, ADAS and the Department for Environment, Food & Rural Affairs (Defra), February 2015

8 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Adegbola Adesogan et al., "Mitigation of greenhouse gas emissions in livestock production," Food and Agriculture Organization (FAO), 2013; Giuliano Cecchi et al., "Assessing the greenhouse gas mitigation effect of removing bovine trypanosomiasis in Eastern Africa," *Sustainability*, 2018, Volume 10, Number 5; M. MacLeod et al., "The greenhouse gas abatement potential of productivity improving measures applied to cattle systems in a developing region," *Animal*, 2018, Volume 12, Number 4; Options for low emission development in the Bangladesh dairy sector, FAO, 2017; *Options for low-emission development in the Kenya dairy sector*, FAO, 2017; *Study to model the impact of controlling endemic cattle diseases and conditions on national cattle productivity, agricultural performance and greenhouse gas emissions*, ADAS and the Department for Environment, Food & Rural Affairs (Defra), February 2015; *Supporting low emissions development in the Ethiopian dairy cattle sector*, FAO, 2017

112 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

0 **Lever implementation cost,** $/$tCO_2e$[1]

Source: *Study to model the impact of controlling endemic cattle diseases and conditions on national cattle productivity, agricultural performance and greenhouse gas emissions*, ADAS and the Department for Environment, Food & Rural Affairs (Defra), February 2015

Note: A 50% move toward "healthy animal status" is assumed as an optimistic scenario in the ADAS research. The 8% greenhouse-gas reduction factor is an estimate which accounts for a 9% yield improvement for applicable portions of the livestock herd.

17 Greenhouse gas– and productivity-focused breeding for livestock

Increased share of animals in production systems with some genetic selection targeting reduced direct methane (CH_4) production per animal, as well as continued selection for productivity improvements (in line with Food and Agriculture Organization [FAO] expected yield gains)

3,181 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

25 **Incremental lever implementation,** % [B]

Source: MarketsandMarkets 2021 data

10 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Abacus Bio; Kath Donoghue et al., "Genomic estimated breeding values for methane production in Australian beef cattle," 21st Biennial Conference of the Association for the Advancement of Animal Breeding and Genetics, September 2015; MarketsAndMarkets 2021 data; M.N. Aldridge et al., "Selective breeding as a mitigation tool for methane emissions from dairy cattle," *Animal*, December 2021, Volume 15; Peter Amer et al., "The potential impact of breeding strategies to reduce methane output from beef cattle," *Animal Production Science*, December 2018, Volume 59, Number 9

81 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

0 **Lever implementation cost,** $/$tCO_2e$[1]

Source: FAOSTAT; OECD

Note: For reduction factor, the weighted average across species (by weight of emissions) is used, where applicable. Peter Amer of AbacusBio was consulted for numerous data points related to this lever, including reduction factor, relative strength of breeding systems, and yield impact.

18 Technologies that increase livestock production efficiencies

Incorporating ionophores in animal feed improves productivity per animal and reduces the amount of methane released per animal

3,168 **Baseline applicable emissions,** million tCO$_2$e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

20 **Incremental lever implementation,** % [B]

Source: Eloize Jaqueline Askel et al., "Growth performance and safety of meat from cattle feedlot finished with monensin in the ration," *Semina: Ciências Agrárias*, March 2018, Volume 39, Number 2; *Greenhouse gas mitigation options and costs for agricultural land and animal production within the United States*, ICF International, February 2013

6 **Greenhouse-gas reduction factor,**[2] % CO$_2$e [C]

Source: Amelia K Almeida, Annette Cowie, and Roger S Hegarty, "Meta-analysis quantifying the potential of dietary additives and rumen modifiers for methane mitigation in ruminant production systems," *Animal Nutrition*, December 2021, Volume 7, Number 4; Karen Beauchemin et al., *An evaluation of evidence for efficacy and applicability of methane inhibiting feed additives for livestock*, Global Research Alliance, November 2021; Mathijs Harmsen, "Non-CO$_2$ greenhouse gas mitigation in the 21st century," Utrecht University, June 21, 2019

80 **Emission-reduction potential,** million tCO$_2$e[1] [A × B × C][3]

(135) **Lever implementation cost savings,** \$/tCO$_2$e[1]

Source: Tara Felix, "Ionophores: A technology to improve cattle efficiency," Penn State Extension, updated February 2017

Note: Interviews with Dr. Amelia de Almeida (University of New England) and Dr. Ermias Kebreab (UC Davis) contributed to the determination of the incremental lever implementation percentage. The 6% greenhouse-gas reduction factor is a combined estimate which accounts for a 4% reduction in emissions for enteric fermentation and a 6% yield improvement for applicable portions of the livestock herd.

19 Heat stress management

Reducing heat stress experienced by animals to improve productivity per animal and to lower animal mortality, improving methane per yield and net methane emissions

3,168 **Baseline applicable emissions,** million tCO$_2$e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

35 **Incremental lever implementation,** % [B]

5 **Greenhouse-gas reduction factor,**[2] % CO$_2$e [C]

Source: Mario Herrero et al., "Impacts of heat stress on global cattle production during the 21st century: A modelling study," *The Lancet Planetary Health*, March 2022, Volume 6, Number 3

57 **Emission-reduction potential,** million tCO$_2$e[1] [A × B × C][3]

(84) **Lever implementation cost savings,** \$/tCO$_2$e[1]

Source: Elizabeth J. Bigler et al., "Impacts of shade on cattle well-being in the beef supply chain," *Journal of Animal Science*, February 2021, Volume 99, Number 2; Perano et al., "Economic Returns for Different Cooling Systems for Dairy Cattle," Animal Environment and Welfare, October 2017; "Practice: 717 - Livestock shade structure," USDA Natural Resources Conservation Service, December 2013; "Livestock shade structure," Natural Resources Conservation Service (NRCS) Florida, September 2008

Note: An interview with Philip Thornton of CCFAS - CGIAR contributed to the determination of the incremental lever implementation percentage. The 6% greenhouse-gas reduction factor is an estimate which accounts for a 6% yield improvement for applicable portions of the livestock herd.

20 Feed grain processing for digestibility

Improving starch digestibility of grain through mechanical processing, which improves productivity and reduces methane-producing enteric fermentation in animals

1,888 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

10 **Incremental lever implementation,** % [B]

Source: Lizzie Bonsall, "Brazilian beef: The China of Latin America?," FoodNavigator-USA, updated July 3, 2015; Mathijs Harmsen, "Non-CO_2 greenhouse gas mitigation in the 21st century," Utrecht University, June 21, 2019; M L Galyean et al., "Nutritional recommendations of feedlot consulting nutritionists: The 2015 New Mexico State and Texas Tech University survey," *Journal of Animal Science*, June 2016, Volume 94, Number 6

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Source: Adegbola Adesogan et al., "Mitigation of greenhouse gas emissions in livestock production," Food and Agriculture Organization (FAO), 2013; "Can two negatives make a positive?," US Department of Agriculture Tellus, accessed January 10, 2023; *Cattle grain processing symposium*, Oklahoma State University, November 2006; Khalil Safaei and WenZhu Yang, "Effects of grain processing with focus on grinding and steam-flaking on dairy cow performance," in *Herbivores*, IntechOpen, March 2017

31 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

1 **Lever implementation cost,** \$/tCO_2e[1]

Source: G.E. Erickson, T.J. Klopfenstein, and C.N. Macken, "The cost of corn processing for finishing cattle," *The Professional Animal Scientist*, February 2006, Volume 22, Number 1; Mathijs Harmsen, "Non-CO_2 greenhouse gas mitigation in the 21st century," Utrecht University, June 21, 2019

Note: The 5% greenhouse-gas reduction factor is a combined estimate which accounts for an 11% reduction in emissions for enteric fermentation and a 6% yield improvement for applicable portions of the livestock herd. Lever implementation cost was calculated with assumptions based on Food and Agriculture Organization (FAO) GLEAM (Global Livestock Environmental Assessment Model) data on stocks and emissions; there are an assumed 6,300,077 dairy cows (24% of which are on grassland), 27,984,676 beef cows (12% of which are on grassland), and 129,732 buffalo (15% of which are on grassland).

21 Shift to higher-fat diet

Expand dry-matter percentage (DM%) of fats in animal diets to reduce methane production

1,820 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

10 **Incremental lever implementation,** % [B]

Source: *OECD-FAO agricultural outlook 2021-2030*, OECD, July 2021

9 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Julia Q Fouts et al., "Enteric methane mitigation interventions," *Translational Animal Science*, April 2022, Volume 6, Number 2

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188 **Lever implementation cost,** \$/tCO_2e[1]

Source: Alex Scott, "DSM seeks approval of additive that minimizes methane from cattle," *Chemical Engineering News*, July 23, 2019

Note: Lever implementation cost was calculated with assumptions based on Food and Agriculture Organization (FAO) GLEAM (Global Livestock Environmental Assessment Model) data on stocks and emissions; there are an assumed 6,300,077 dairy cows (24% of which are on grassland) and 27,984,676 beef cows (12% of which are on grassland).

22 Decrease forage-to-concentrate ratio

Decreasing the amount of forage and increasing the grain concentrates as a proportion of diet, leading to a decrease in methane emissions

3,168 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

20 **Incremental lever implementation,** % [B]

Source: Bruce Greig, "Aspects of South American dairying," South Island Dairy Event, May 2006; *OECD-FAO agricultural outlook 2021-2030: Meat*, OECD, July 2021

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Source: Claudia Arndt et al., "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," *Sustainability Science*, May 2022, Volume 119, Number 20

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(306) **Lever implementation cost savings,** $/$tCO_2e$[1]

Source: Larry Muller and Peter Tozer, "Economics of supplemental feeding with pasture-based systems," Penn State Extension, updated May 9, 2016

Note: The 8% greenhouse-gas reduction factor is an estimate based on a 9% yield improvement for applicable portions of the livestock herd. Lever implementation cost savings assumes an average cow of 1,000 lbs; intake at 0.5% body weight = 5 lbs. Lever implementation cost was also calculated with assumptions based on Food and Agriculture Organization (FAO) GLEAM (Global Livestock Environmental Assessment Model) data on stocks and emissions; there are an assumed 6,300,077 dairy cows (24% of which are on grassland) and 27,984,676 beef cows (12% of which are on grassland).

23 Feed additives

We evaluated 3 feed additives as potential levers for reducing emissions, primarily methane, from livestock. These solutions included 3-nitrooxypropanol (3-NOP), red seaweed, and hydrogen (H_2) electron sinks (nitrates). Because the scale of implantation for each is not yet clear, we have combined them as a single lever for simplicity:

- 3-NOP is a feed additive that blocks enzymes needed for methanogenesis, thus decreasing methane production in ruminants
- Nitrate feed additives reduce the amount of methane produced in the intestinal lumen of livestock, reducing methane emissions
- Inclusion of freeze-dried red seaweed (Asparagopsis taxiforma) in livestock feed diets suppresses methanogenesis and reduces the amount of methane emitted

1,820 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

25 **Incremental lever implementation,** % [B]

Source: Defined in Hannah Ritchie and Max Roser, “Farm size and productivity,” Our World in Data, 2022 and assuming adoption rates of 70% in US, EU, Brazil, Australia, and New Zealand and 20% in Asia, Africa, and other Latin American countries

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350 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

99 **Lever implementation cost,** $/$tCO_2e$[1]

Source: “Commission implementing regulation (EU) 2022/565 of 7 April 2022 concerning the authorisation of a preparation of 3-nitrooxypropanol as a feed additive for dairy cows and cows for reproduction,” *Official Journal of the European Union*, April 2022; expert interviews; Karen Beauchemin et al., *An evaluation of evidence for efficacy and applicability of methane inhibiting feed additives for livestock*, Global Research Alliance, November 2021; The USDA’s National Organic Program dry matter intake recommendations

Note: Lever implementation cost was calculated with assumptions based on Food and Agriculture Organization (FAO) GLEAM (Global Livestock Environmental Assessment Model) data on stocks and emissions; there are an assumed 6,300,077 dairy cows (24% of which are on grassland) and 27,984,676 beef cows (12% of which are on grassland). Final values may not exactly match A x B x C calculations, because of rounding.

24 N-inhibitors and urease inhibitors on pasture

Nitrate feed additives reduce the amount of methane produced in the intestinal lumen of livestock, reducing methane emissions

860 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

55 **Incremental lever implementation,** % [B]

Source: Mathijs Harmsen, "Non-CO_2 greenhouse gas mitigation in the 21st century," Utrecht University, June 21, 2019

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34 **Lever implementation cost,** $/$tCO_2e$[1]

Source: "Efficiency of two nitrification inhibitors," 2016; FAO for livestock density based on global pastureland and animals raised on pastureland

Note: Final values may not exactly match A x B x C calculations, because of rounding.

25 Large-scale anaerobic manure digestion

Capture and utilization of greenhouse gases through large-scale digesters (complete mix, plug flow, and anaerobic covered-lagoon digesters) primarily in mature economies

236 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

40 **Incremental lever implementation,** % [B]

Source: Wina H.J. Crijns-Graus, Mirjam Harmelink, and Chris Hendriks, "Marginal GHG-abatement curves for agriculture," Ecofys, April 2004

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Source: Ignacio Perez Dominguez et al., "An economic assessment of GHG mitigation policy options for EU agriculture," European Commission Joint Research Centre, 2016; Robert Beach et al., "Methane and nitrous oxide mitigation in agriculture," *The Energy Journal*, 2006, Volume 27; Robert Beach et al., "Structural change as a key component for agricultural non-CO_2 mitigation efforts," *Nature Communications*, March 2018, Volume 9, Number 1060.

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311 **Lever implementation cost,** $/$tCO_2e$[1]

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Note: For lever implementation cost, capital expenditure assumes straight-line depreciation (15-year lifetime).

26 Small-scale anaerobic manure digestion

Capture and utilization of greenhouse gases through small-scale digesters, primarily in maturing economies and locations with smaller livestock herds

236 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

20 **Incremental lever implementation,** % [B]

Source: Wina H.J. Crijns-Graus, Mirjam Harmelink, and Chris Hendriks, "Marginal GHG-abatement curves for agriculture," Ecofys, April 2004

50 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: Ignacio Perez Dominguez et al., "An economic assessment of GHG mitigation policy options for EU agriculture," European Commission Joint Research Centre, 2016; Robert Beach et al., "Methane and nitrous oxide mitigation in agriculture," *The Energy Journal*, 2006, Volume 27; Robert Beach et al., "Structural change as a key component for agricultural non-CO_2 mitigation efforts," *Nature Communications*, March 2018, Volume 9, Number 1060.

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1,000+ **Lever implementation cost,** $/$tCO_2e$[1]

Source: B. Wade Brorsen and Cortney Cowley, "Anaerobic digester production and cost functions," *Ecological Economics*, October 2018, Volume 152; *Greenhouse gas mitigation options and costs for agricultural land and animal production within the United States*, ICF International, February 2013; Richard Blanchard and Alun Scott, "The role of anaerobic digestion in reducing dairy farm greenhouse gas emissions," *Sustainability*, March 2021, Volume 13, Number 5; US Environmental Protection Agency data on share of existing facilities

Note: For lever implementation cost, capital expenditure assumes straight-line depreciation (15-year lifetime).

27 Improved fuel efficiency in fishing vessels

Improved fuel efficiency of fishing vehicles through reduction in drag (eg, from fishing gear), new vessel design, route optimization, and speed optimization

34 **Baseline applicable emissions,** million tCO_2e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

65 **Incremental lever implementation,** % [B]

Source: McKinsey analysis

25 **Greenhouse-gas reduction factor,**[2] % CO_2e [C]

Source: James F. Muir, "Fuel and energy use in the fisheries sector," Food and Agriculture Organizations of the United Nations, 2015; Lee Kindberg, "Improving vessel and supply chain fuel efficiency," Mobile Sources Technical Review Subcommittee (MSTRS), April 19, 2012; Odd Magnus Faltinsen et al., "The influence of route choice and operating conditions on fuel consumption and CO_2 emission of ships," *Journal of Marine Science and Technology*, January 2016, Volume 21

6 **Emission-reduction potential,** million tCO_2e[1] [A × B × C][3]

(22) **Lever implementation cost savings,** $/$tCO_2e$[1]

Source: Source: James F. Muir, "Fuel and energy use in the fisheries sector," Food and Agriculture Organization of the United Nations, 2015; Odd Magnus Faltinsen et al., "The influence of route choice and operating conditions on fuel consumption and CO_2 emission of ships," *Journal of Marine Science and Technology*, January 2016, Volume 21

Note: Lever implementation cost savings are estimated based on energy expenditure associated with the emissions total sourced from the Food and Agriculture Organization and converted into fuel savings. Fuel prices are regionalized used the global diesel price index.

28 Conversion to hybrid and electric fishing vessels

Conversion of gasoline-powered fishing vessels to electric or hybrid-electric systems; primarily applicable for new fishing vehicles due to high capital expenditure requirements

34 **Baseline applicable emissions,** million tCO$_2$e,[1] 2050 [A]

Source: FAOSTAT 2022; McKinsey analysis

60 **Incremental lever implementation,** % [B]

Source: McKinsey analysis

50 **Greenhouse-gas reduction factor,**[2] % CO$_2$e [C]

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5 **Lever implementation cost,** \$/tCO$_2$e[1]

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Note: Incremental lever implementation percentage is based on a fishing vessel engine lifetime of about 30 years. For lever implementation cost, fuel use data was converted to liters of diesel fuel equivalents at a price of $1.35/liter; the cost of electricity to produce the equivalent amount of energy was subtracted at a rate of $133.90/MWh.

[1] Metric tons of carbon dioxide equivalent.
[2] Difference due to greenhouse-gas reduction factor, % rounding.
[3] Final values may not exactly match A x B x C calculations due to rounding to whole values.

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