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Feeding the world sustainably

Green technologies, biotech advances, and artificial intelligence could help tame agricultural emissions and waste, while safeguarding ocean resources.

A burst of technology in the 1960s—the Green Revolution—raised agricultural output significantly across developing economies. Since then, rising incomes have boosted protein consumption worldwide, and elevated new challenges: greenhouse-gas emissions from agriculture are increasing (more than a fifth of all emissions worldwide), while a host of practices, from waste to overfishing, threaten the sustainability of food supplies. The COVID-19 pandemic has brought these concerns to the fore: the disease has disrupted supply chains and demand, perversely increasing the amount of food waste in farms and fields while threatening food security for many.

As agriculture gradually regains its footing, participants and stakeholders should be casting an eye ahead, to safeguarding food supplies against the potentially greater and more disruptive effects of climate change. Once again, innovation and advanced technologies could make a powerful contribution to secure and sustainable food production. For example, digital and biotechnologies could improve the health of ruminant livestock, requiring fewer methane-producing animals to meet the world's protein needs. Genetic technologies could play a supporting role by enabling the breeding of animals that produce less methane. Meanwhile, AI and sensors could help food processors sort better and slash waste, and other smart technologies could identify inedible by-products for reprocessing. Data and advanced analytics also could help authorities better monitor and manage the seas to limit overfishing—while enabling boat crews to target and find fish with less effort and waste. Agriculture is a traditional industry, but its quest for tech-enabled sustainability offers valuable lessons.

Agriculture takes center stage in the drive to reduce emissions

Cross-sector investment opportunities will lead the way.

by Daniel Aminetzah, Joshua Katz, and Peter Mannion

More than one-fifth of the world's greenhouse-gas (GHG) emissions stem from agriculture—over half from animal farming.[1] Unless these emissions are actively addressed, they will probably increase by 15 to 20 percent by 2050 as the Earth's population rises and the need for food continues to grow. Limiting the impact of climate change will require shifts in what we eat, how much we waste, and how we farm and use our land.

There is no clear path to fully eliminating agricultural emissions. Nonetheless, a wave of transformation is within reach of the food industry and the broader agricultural market. Historically, agricultural innovation has arisen at points of intersection with other industries as creative firms borrowed and built on advances in areas such as human health, chemicals, advanced engineering, software, and advanced analytics. Cross-cutting opportunities portend the next wave of innovation to reduce agricultural emissions by capturing food-process efficiencies (exhibit).

While the abatement costs vary and the market opportunities continue to evolve, mitigation measures could reduce emissions by about 20 to 25 percent by 2050.[2] In this article, we highlight the top three cost-negative or cost-neutral measures in which business actors will play a critical role. Scaling up these solutions will require investment, technological innovation, and behavioral change—particularly among farmers around the world.

Zero-emissions farm equipment

The largest amount of emissions abatement from a single measure can be achieved by shifting from traditional fossil-fuel equipment—such as tractors, harvesters, and dryers—to their zero-emission counterparts. This transition alone would realize cost savings of $229 per ton of carbon-dioxide equivalent (tCO_2e)[3] and transform the $139 billion global agricultural-equipment industry.

Unfortunately, the current market penetration of zero-emission equipment is lower in farming than it is in consumer vehicles: market leaders are only at the stage of piloting proofs of concept. The right investments by machinery manufacturers would make it possible to achieve total-cost-of-ownership parity between, for example, tractors powered by internal-combustion engines and tractors powered by zero-emissions sources (such as battery

[1] Does not include land use, land-use change, and forestry. Non-CO_2 emissions converted using 20-year global-warming-potential (GWP) values based on the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC).

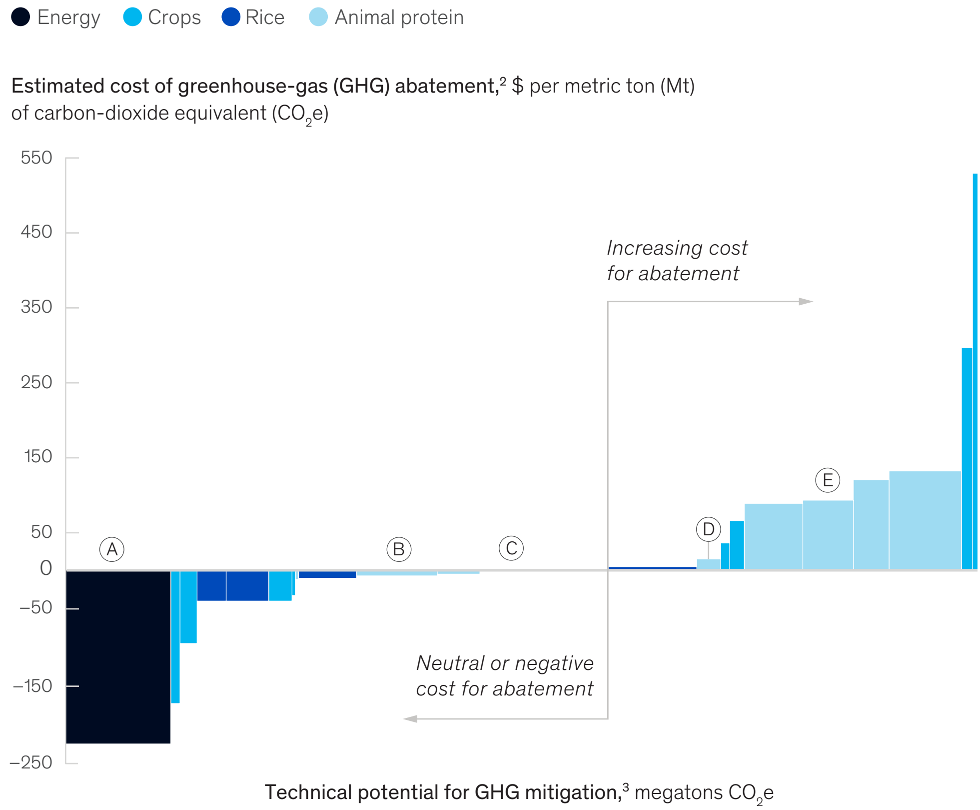
[2] For more, see Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, and Peter Mannion, "Reducing agriculture emissions through improved farming practices," May 2020, McKinsey.com.

[3] Used to compare emissions of greenhouse gases.

Exhibit

Abatement measures in agriculture open up cross-sector opportunities—including opportunities that either save money or are cost neutral.

Top 25 mitigating measures for agriculture[1] and associated abatement costs



Some abatement measures offer cross-sector investment opportunities beyond agriculture. For example:

(A) Automotive
Transition to zero-emissions farm machinery and equipment
–$229/Mt$CO_2$e

(B) Animal health/ pharmaceutical
Improved health monitoring and illness prevention
–$5/Mt$CO_2$e

(C) Genetics
GHG-focused breeding and genetic selection
0/MtCO_2e

(D) Chemicals
Apply nitrification inhibitors on pasture
+$15/Mt$CO_2$e

(E) Energy
Expand use of anaerobic manure digestion
+$92/Mt$CO_2$e

[1] Implementing all 25 measures would reduce GHG emissions from agriculture by 20%.
[2] Based on 20-year global warming potential (GWP) cited in fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC).
[3] Based on 100-year GWP cited in IPCC's fifth assessment report.

electric power) by around 2030.[4] Like early investors in passenger electric vehicles (EVs), investors in agricultural EV technology are now poised to benefit from first-mover advantage. AGCO's Fendt, Rigitrac, and Escorts' Farmtrac each showcase electric-tractor models, and John Deere has battery-run and corded electric-tractor prototypes. If electric farm equipment captured just 10 percent of the 2030 market, this would represent an opportunity of $13 billion.

Battery capacity and charging speeds have been the main obstacles to the adoption of electric farm equipment. However, battery weight is less problematic for farm equipment than for passenger vehicles. A rapid reduction in prices for batteries, which alone account for up to 40 percent of tractor-component costs, will help further overcome adoption barriers.[5]

Animal health monitoring

As our colleagues have noted, achieving a 1.5-degree warming pathway[6] would require a significant reduction in human consumption of animal protein (for more, see "Climate math: What a 1.5-degree pathway would take," on McKinsey.com). The agricultural sector has a major role to play by meeting the world's animal-protein needs with fewer, healthier animals that generate lower emissions from enteric fermentation and by improving manure management. These steps could reduce emissions by more than 400 million tons of carbon-dioxide equivalent ($MtCO_2e$) by 2050 (realizing savings of $5 per tCO_2e) and generate productivity benefits that would improve agricultural economics.

Emerging biological technologies and computational capabilities, such as gene sequencing and artificial intelligence, enable farmers to detect disease early—and even prevent it—by applying predictive algorithms to existing and new sources of data. For example, Moocall, an Irish company collaborating with Vodafone, aims to reduce cow mortality rates from birth-related complications by up to 80 percent by placing (on the animal's tail) a palm-sized sensor alerting farmers to how long a cow has been calving. In North America, which has the third-largest cow inventory (after Brazil and China), overall cattle-herd productivity improvements could reach 8 percent.[7]

However, implementing these technologies has proved to be expensive, and they are not yet well understood or embraced by farmers. Moreover, health challenges vary greatly by region and species, so a silver bullet is unlikely. Innovative business models and commercial investment will be required to overcome these barriers: for example, the global technology company Fujitsu has developed an algorithm-based "connected cow" service to make milk production more profitable.[8] We expect more commercial investment in coming years, given the continued decline in the cost of such technologies and their multiple applications, including new vaccinations and advanced diagnostics.

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[4] See Markus Forsgren, Erik Östgren, and Andreas Tschiesner, "Harnessing momentum for electrification in heavy machinery and equipment," April 2019, McKinsey.com.

[5] See Forsgren et al., "Harnessing momentum."

[6] A 1.5-degree pathway is an estimate of the extent of change required by each sector of the global economy to curb increases in greenhouse-gas emissions sufficiently and limit temperature increases in the years ahead to 1.5 degrees Celsius above preindustrial levels—a level of increase that, scientists estimate, would reduce the odds of initiating the most dangerous and irreversible effects of climate change.

[7] "Study to model the impact of controlling endemic cattle diseases and conditions on national cattle productivity, agricultural performance and greenhouse gas emissions," ADAS, February 2015, randd.defra.goc.uk.

[8] "Akisai Food and Agriculture Cloud GYUHO SaaS (cattle breeding support service)," Fujitsu, fujitsu.com.

GHG-focused breeding

New breeding programs using sophisticated genetic-selection capabilities can help curb enteric fermentation, potentially reducing overall emissions by 500 $MtCO_2e$ at virtually no cost by 2050. Today, breeding for methane efficiency has achieved a 20 percent variation in methane production. More GHG-focused programs will be possible as increasing demand for animal protein continues to drive growth in the animal genetic-products market (worth $4.2 billion in 2018).

While genetic-breeding programs are still in their infancy, government and industry are leading the effort to drive adoption. In November 2019, a consortium funded by the New Zealand agricultural sector and the country's government launched a "global first" genetics program to breed sheep that produce less methane per mouthful of grass.[9] Even with such programs, large-scale adoption throughout the industry will require economic incentives: market payments or credits for methane reductions.

To implement solutions at scale, additional investments will be needed in genetic-selection capabilities to address the immaturity and lack of breed-specificity of most genetic programs. New breeding techniques, such as those using CRISPR-Cas9,[10] could lower barriers to entry for innovators and allow for more specificity.

A new agricultural ecosystem will be needed to mitigate the increase in agricultural GHG emissions while meeting the world's food needs. In the near term, the reduction of emissions will depend largely on today's technologies and opportunities. But next-horizon technologies (such as gene editing, novel feed additives, and aerobic rice) are also needed. Players in industries ranging from automotive and energy to pharmaceuticals have important roles to play. It will take a village to feed our global village. Q

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For the full report on which this article is based, see "Reducing agriculture emissions through improved farming practices," on McKinsey.com.

[9] "Sheep farmers now able to breed 'low-methane' sheep," Pastoral Greenhouse Gas Research Consortium, pggrc.co.nz.

[10] A new technology that allows editing of DNA sequences.

Using artificial intelligence in the fight against food waste

AI can help accelerate the move toward a circular economy in the agricultural sector.

by Anna Granskog, Eric Hannon, and Chirag Pandya

Roughly one-third of all food is wasted before it is consumed by people. The methane emissions that result are 86 times more potent in driving temperature increases than CO_2 emissions are, when looking over a 20-year time frame.[1] Emerging applications for artificial intelligence (AI) are helping to create opportunities for "designing out" food waste in the value chain: from farming, processing, and logistics to consumption. In effect, AI can accelerate the transition to an agricultural circular economy, in which growth is decoupled from the consumption of finite resources. Circular-economy principles, which historically have taken root slowly and gradually, rest on designing out waste and pollution, keeping products and materials in use, and regenerating natural systems. Here are three areas where AI has the potential to jump-start a circular economy in agriculture, while potentially unlocking more than $100 billion in value for players globally.[2]

Efficient farming practices

AI can help farmers avoid expensive and time-consuming field trials by identifying the best-performing regenerative agriculture practices. For example, CiBO Technologies uses data analytics, statistical modeling, and AI to simulate field trials and agricultural ecosystems under different conditions. Global stakeholders could learn to improve profitability and sustainability by exploring possible outcomes virtually without the risk of damaging the environment or sacrificing yield. Combining AI algorithms with robotic technologies can further automate and increase control in the farming process. For instance, AI can be used to interpret images of crops, such as strawberries, to help determine when food should be harvested; the harvesting, in addition, can be done with autonomous robots. This might reduce food waste in the field, and it could enable more accurate yield forecasting by improving information along the supply chain and by maximizing storage and cooling facilities.

Reducing food waste

AI algorithms can help with food sorting during processing by analyzing images and data from cameras, X-rays, lasers, and near-infrared spectroscopy. The ability to automatically sort nonuniform produce, such as carrots and potatoes, can reduce waste by sorting for best use, size, shape, and quality, removing a manual process that can be time consuming,

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[1] Francois-Marie Breon et al., "Anthropogenic and natural radiative forcing," *AR5 climate change 2013: The physical science basis*, Intergovernmental Panel on Climate Change (IPCC), 2013, fifth assessment report, Chapter 8, ipcc.ch.

[2] For more, see *Sustainability blog*, "How AI can unlock a $127B opportunity by reducing food waste," blog entry by Clarisse Magnin, March 27, 2019, McKinsey.com.

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expensive, and inaccurate. Some companies, such as Wasteless, are helping supermarkets and other retailers sell food before the expiration date by using AI-enabled tracking and dynamic pricing. In institutional and restaurant settings, new tools are now being used to capture, track, and categorize data on food waste. What's more, algorithms can forecast and predict sales, enabling restaurants, retailers, and other hospitality institutions to connect supply to demand more effectively.

Repurposing inedible nutrients

Even if all surplus food were redistributed, a large volume of inedible by-products, along with food waste, would continue to be generated. Could these organic materials contain value that could be repurposed? The Massachusetts Institute of Technology's Senseable City Lab and the Alm Lab, for instance, are offering a glimpse of the potential with their Underworlds prototype smart-sewage platform. The platform combines physical infrastructure and biochemical measurement technologies with artificial intelligence to interpret and act on findings about the pathogens in human sewage; eventually this knowledge could repurpose sewage for use in regenerative food systems.

AI is poised to play an important role for agriculture in the transition to a circular food system. It could revolutionize the way food is grown, harvested, distributed, and enjoyed. As more data sources become available and as computational capabilities grow, AI could help match food supply and demand more effectively, improve supply-chain efficiency, and curb overproduction, overstocking, and waste. Q

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Making fisheries sustainable—and profitable—with advanced analytics

Data and digital technologies could transform a traditional industry while helping stem the damage to ocean ecosystems.

by Julien Claes, Elin Sandnes, and Antoine Stevens

Gathering data and applying the power of advanced analytics can help tackle problems in surprising ways. The distressed state of the oceans is a case in point. Decades of overfishing is depleting the oceans at an alarming rate, at a time when the emerging world increasingly depends on seafood for protein. Finding a more sustainable means of fishing while preserving ocean ecosystems is a sprawling problem. The fishing industry is feeling the effects: today, it takes five times the effort to haul in a catch as it did in 1950.[1] We looked at how fisheries, government authorities, and food companies could deploy advanced analytics to improve monitoring and raise the efficiency of their operations. In addition to giving the fishing industry new tools for more profitable, sustainable operations, there's also a climate bonus: reeling in a ton of fish protein has less than a tenth of the greenhouse-gas intensity of equivalent protein harvested from ruminant livestock.

Oceans in danger

The demand for fish is growing twice as fast as the world's population growth rate. As boats trawl for a profitable haul, they are moving into new and deeper waters. Yet the catch is declining, with aquaculture rising steadily to meet demand (Exhibit 1). The effect on the ecosystem is stark: half of the world's fish species stocks are overexploited, rebuilding, or collapsing (Exhibit 2). This degradation in biodiversity comes on top of the effects of climate change, which are warming oceans and changing their chemistry.

Recognizing the threats, national governments have moved to strengthen and improve management and regulation. Yet regional gains often are negated by overfishing or illegal catches in adjacent zones. Many of today's efforts, including reporting of catches, industry information sharing, and regulatory enforcement, could be bolstered by tighter collaboration.

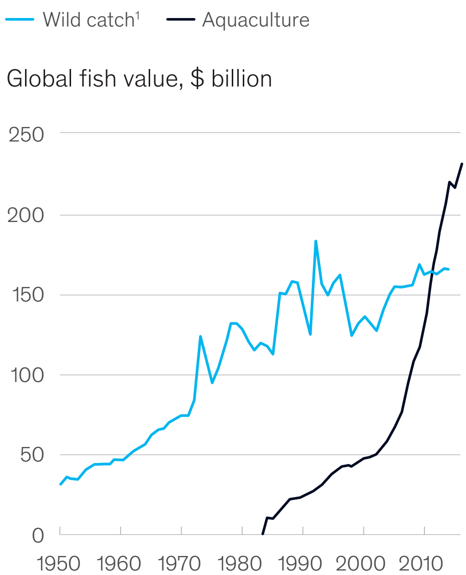
A bounty of data

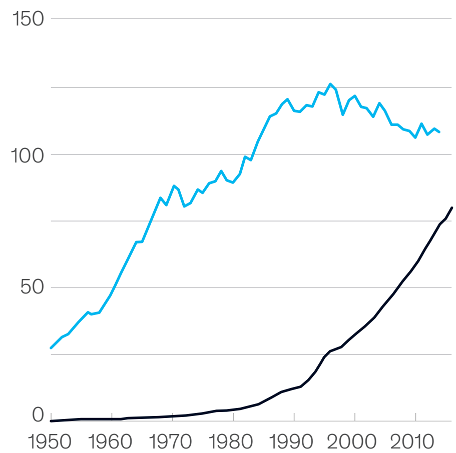
Much like agriculture onshore, the fishing industry is geographically dispersed with operators large and small. Farmers plow their fields guided by data on weather and soil conditions. While most fisheries still operate in a traditional way, something similar is starting to take shape in fishing. Radar and optical sensors on satellites can pick up patterns in the ocean environment such as temperature and signals of fish movements. While that information is valuable for fisheries, it also helps authorities track boat

[1] Measured in kilowatt-hours expended.

Exhibit 1

As wild-fish capture has declined, aquaculture has risen to meet demand.





[1] Excludes aquatic mammals; alligators, caiman, and crocodiles; seaweeds; and other aquatic plants.

Source: Food and Agriculture Organization of the United Nations; Sea Around Us, University of British Columbia and the University of Western Australia, 2014

locations and movement. Camera-equipped drones, meantime, operating not only in the air but undersea, give some boats today a more comprehensive view of nearby fishing conditions. Looking forward, advanced sensors and monitors could automatically collect data on the gear used, species caught or discarded, volume of hauls, and more that's often done by fishermen. Governments, meanwhile, have pushed for better data to help keep watch on illegal fishing, mandating that larger vessels be equipped with monitoring systems that transmit location, speed, and direction.

Over time, much more information could be integrated with Internet of Things technologies that link sensors to satellite- and land-based communications networks. Crunching the data by using advanced analytics and machine learning would ultimately help balance competing interests—helping fisheries manage a risky, volatile business while providing authorities with better information for policing and shaping sustainability policies.

Turning the tide with analytics

Let's look on deck. Boat captains with larger commercial fisheries have used technologies such as sonar, though many still rely on intuition, experience, and basic observations to navigate and detect fish. Contrast that with what's potentially ahead: fish detection supported by targeted analytic models that could provide daily forecasts for entire fishing territories, helping to track species that are in high demand. And Internet of Things sensors that monitor ocean conditions could help boats define optimal, energy-efficient routes.

Then there's the catch itself. Fishermen often have low visibility into what's in their nets until its pulled onboard—leading to waste. Intelligent sensors of the future will allow crews to automatically and continually monitor parameters such as species and fish size. One analytics tool that larger companies already are using factors in sea temperatures and plankton clusters to model where fish will be, lowering costs for targeting desired species and reducing waste. Poorer regions stand to benefit as well. Fishermen in emerging markets are already gaining greater access to market information by using their cell phones.

On shore, fisheries managers often plan operations hobbled by data scarcity—using landed catches that furnish little forward visibility. Analytics tools promise to offer a more dynamic view of fleets, allowing managers to guide boats and continually monitor stocks. Automatic scanning and intelligent systems that monitor product quality could replace manual sorting of catches. Quality and traceability loom large, as sustainability-conscious consumers demand greater transparency into how and where fish are caught. What's ahead? Researchers are investigating tagging fish using radio frequency identification (RFID) and certifying catches with distributed ledger technologies (blockchain).

For authorities, analytics can help bridge a different gap. Information on fishing activity is partial at best, and coordination among multiple stakeholders—governments, industry, and NGOs—is challenging. That said, sharing the flow of information from advanced monitoring technologies would give authorities a real-time vision of global fishing activities. It would also help them design more efficient surveillance plans across territorial waters. Decentralized, reliable information-management systems requiring little human intervention could ease adoption. One example: analytics-software tools can flag when a boat slows down in a no-take zone, alerting authorities to the suspicious behavior. NGOs are helping to change mindsets. To promote sustainability research, Global Fishing Watch distributes information gleaned from government and satellite data on more than 65,000 fishing vessels. Over time, shared, detailed catch data from cameras and image-recognition software powered by

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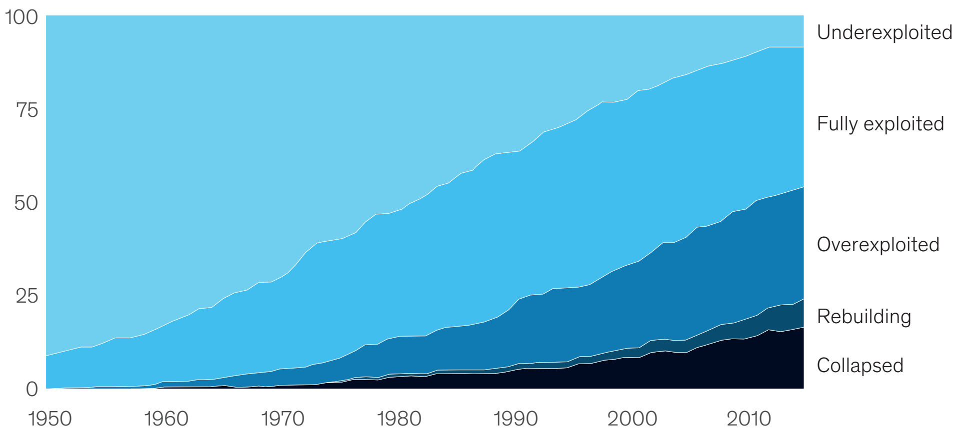
Exhibit 2

Nearly half of the world's fish stocks are overexploited, rebuilding, or have collapsed.

Status of global wild-fish stock,[1] %



[1] Stock status is evaluated by looking at the trends displayed by the lines separating the categories, rather than the vertical % values, due to the imprecise/changing definitions of the categories. Rebuilding stocks are stocks recovering from collapsed status.

Source: Sea Around Us, University of British Columbia and the University of Western Australia, 2014

artificial intelligence will help governments fine-tune regulations and fishing quotas more dynamically to manage ocean resources.

Looking ahead

Our modeling research suggests that for fisheries, there are financial incentives for analytics-guided strategies. We found that optimizing fishing activity over an entire season, monitoring of equipment to minimize downtime, identifying fuel economies from analyzing navigation data, and implementing information-based labor efficiencies could reduce industry costs by $11 billion, or just under 15 percent of today's spending.

For governments, one obstacle will be confronting geopolitical challenges. Some bad actors will continue efforts to game a system where the regulatory map has gaps and where some nations benefit by turning a blind eye to wayward fisheries. Better data and analytics capabilities should move the enforcement needle, helping pinpoint hot spots where illegal fishing continues and identifying chronic offenders for enforcement action. The benefits of data sharing and better analytics tools, meanwhile, will continue to align the interests of fisheries and governments for better resource management. An era of precision fisheries will be key to sustaining the oceans' riches. Q

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For more, see "Precision fisheries: Navigating a sea of troubles with advanced analytics," on McKinsey.com.

The quest for sustainable proteins

Concerns about health, animal welfare, and climate are bolstering interest in a range of alternative proteins.

by Jordan Bar Am, Zafer Dallal Bashi, and Liane Ong

Meat has always been a protein mainstay for human beings—the main source in developed markets and a rising one in developing markets as they get richer. In recent years, meanwhile, consumer awareness and interest in alternative-protein sources has grown steadily. That's particularly true in wealthier countries, where a desire for better health and animal welfare, along with environmental concerns, are shaping preferences. On the last point, our colleagues have shown that proteins produced from ruminant livestock (cows and sheep) are 30 times more greenhouse-gas intensive than those from vegetable proteins. In fact, if cows were classified as their own country, they would emit more greenhouse gases than any country except China.[1]

Sources of alternative proteins include a mix of plant-based proteins (soy, pea), new animal sources (insects), biotechnological innovations (lab-cultured meat), and mycoproteins (derived from fungi). Several entrants in the alternative-protein industry are rolling out new technologies and ingredients, looking to lock in leading positions in a growing market. (For interviews with executives and entrepreneurs at companies breaking ground in alternative-proteins, see "The future of food: Meatless?," on McKinsey.com.) Consumers tend to find the recent protein innovations appetizing, and companies are fueling awareness with aggressive marketing efforts.

While aggregate consumption of meat-based proteins worldwide continues to grow, a shift in preferences may be one reason (among several) why meat's overall growth rate is expected to decline by half over the next decade. Sales of plant-based food (the largest source of alternative protein) rose 17 percent in the United States in 2018,[2] and the use of alternative protein as a food ingredient is predicted to continue growing. Alternative proteins, of course, are still a small slice of the market for meat ($2.2 billion compared with approximately $1.7 trillion, respectively[3]). But innovation is rife. The share of new products released with an alternative-protein claim grew from 2 percent to more than 5 percent of the market from 2007 to 2016, according to market researcher Mintel, while consumer interest in alternative-protein products and diets, as measured by online-search results, has increased markedly in many cases.

A look at four types of alternative proteins highlights trends in demand and innovation

[1] See Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, and Peter Mannion, "Reducing agriculture emissions through improved farming practices," May 2020, McKinsey.com.

[2] Caroline Bushnell, "Newly released market data shows soaring demand for plant-based food," the Good Food Institute, September 12, 2018, gfi.org.

[3] Food and Agriculture Organization of the United Nations, June 3, 2019, fao.org.

and suggests where meat protein trends might be heading.

Pea protein

Pea protein is expected to lead the alternative-protein market in the short and medium term, though the product faces certain challenges. The past few years witnessed a limited supply of pea protein caused by a shortage in processing capacity. Producers of mainstream products such as veggie burgers will likely use soybean protein, where input costs are lower and supplies are more stable. However, high-end products will likely use pea protein to cater to consumer expectations of a niche ingredient, which is a product that touts health claims and is for sale at a premium price.

Cultured meat

Lab-grown cultured meat seeks to mimic the muscle tissue found in animals and has the same protein profile (and taste). The industry has received funding from a variety of sources including industry players. The cultured-meat industry is well positioned for the future, even with major technical challenges to overcome, including the difficulties in the development of an immortal cell line and recycling of blood ingredients, both of which help keep costs down. Scientists have been working on this protein since 2013, when the first lab-grown burger made its public debut. The price of cultured meat has already decreased significantly in the past nine years (the first lab-grown hamburger cost $325,200 in 2013 and then decreased to around $11 in 2015, with estimates from some cultured-meat companies indicating that costs will drop to less than $10 per pound by 2022).[4]

Insect and mold protein

Crickets are the most common source of edible insects and a good source of protein. They have long been a dietary staple in many areas of Asia, Latin America, and Africa. Some producers are milling crickets for flour. However, it is currently cost prohibitive to isolate protein from the flour as the cost of the crickets is high, making the process difficult to scale. Some food producers are exploring grasshoppers as an edible protein, and a range of insect proteins are likely to be suitable for use in animal feed. Mold protein, meanwhile—or mycoprotein—is typically composed of whole, unprocessed, filamentous fungal biomass, commonly known as mold. It is mixed with eggs to create a meat-like texture for commercial products. It has been around since the 1980s and is produced through fermentation of biological feedstock. Mycoproteins are sold as a meat substitute primarily in Europe, and interest is growing in the US market as well, though consumer interest is still dampened by negative perceptions.

Animal protein will likely continue to dominate the market, driven by key advantages such as customer familiarity. However, there is room at the table for plant-based products, as evidenced by growing shifting customer concerns around traditional meat protein. Q

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→ *For more, see "Alternative proteins: The race for market share is on," on McKinsey.com.*

[4] Amelia Lucas, "Lab-grown meat start-up raises $14 million to build production plant," CNBC, October 10, 2019, cnbc.com.