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Gene Editing for the Climate: Biological Solutions for Curbing Greenhouse Emissions

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Recent advances in gene editing offer promising opportunities to mitigate emissions from agriculture and other sectors, and to capture carbon from the atmosphere. Governments should accelerate the development and deployment of these solutions.

KEY TAKEAWAYS

- Gene editing has emerged in the past decade as a platform technology with enormously broad potential. It is a powerful new toolkit for developing clean energy and climate solutions that policymakers have so far under-emphasized.
- Gene editing could enhance the efficiency of photosynthesis, reduce methane emissions from cows and rice paddies, optimize biofuel crops, and solve many other climate challenges.
- Governments should move with urgency to eliminate unscientific regulatory burdens on gene editing that impede and disincentivize innovation, while contributing little to human or environmental safety.
- To accelerate the development and deployment of gene-edited clean energy and climate solutions, governments should increase investment and improve coordination of R&D, and expand incentives for adopting the technology.

INTRODUCTION

Excess emissions of greenhouse gases (GHGs) from human activities have accumulated in the atmosphere at levels sufficient to disrupt global patterns of heat exchange, driving changes in climate and weather with dramatic, detrimental consequences.[1] Meanwhile, over the past half-century, advances in biology have enabled humans to adapt the genetic blueprints of life in new ways, and to an unprecedented degree. The former presents a serious threat to the global economy, human health, and the environment. The latter offers solutions that can play an important role in limiting future GHG emissions and removing past emissions from the atmosphere.

This report explores solutions made possible by the most modern techniques of biotechnology: gene editing. An esoteric interest of just a handful of molecular biologists only a decade ago, gene editing is now the second-most published topic in biology (after SARS-CoV-2/COVID-19). Gene editing can be used to improve fundamental biological processes, like photosynthesis, to deliver positive impacts across wide range of human activities, including those that impact the climate.

Noted physicist Freeman Dyson wrote in 2008, "After we have mastered biotechnology, the rules of the climate game will be radically changed…. if we can control what the plants do with the carbon, the fate of the carbon in the atmosphere is in our hands."[2] While Dyson's long-term prediction will not quickly come to pass, over the next 50 years, gene editing will make significant contributions to address the climate challenge, especially if public policymakers recognize and act on the opportunity quickly. Public investments in climate and clean energy research, development, and demonstration (RD&D) to date have focused heavily on chemical and physical solutions. It's time for biology to play a much bigger role.

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This report describes how ancient biological processes have been reforged by researchers into new tools that can reshape the characteristics of plants, animals, and microbes to help reduce GHG emissions and remove carbon dioxide from the atmosphere. It focuses primarily on opportunities for agricultural innovation, which is the logical sector for initial applications because, while it is not the largest source of GHGs, it is more directly dependent on biology than other sectors.[3] The report also addresses biofuels, before turning to applications of gene editing that hold promise for removing carbon from the atmosphere.

It concludes with a set of policy recommendations aimed at accelerating the development and deployment of gene-edited climate solutions, making four key recommendations to the United States government and its international partners:

1. Eliminate unscientific regulatory burdens and barriers that hinder the development of safe gene-edited products.
2. Increase investment in research and development (R&D) priorities such as advancing CRISPR tools, enhancing photosynthesis, and improving methods to measure soil carbon.

3. Improve coordination of existing R&D efforts within the United States and around the world.

4. Expand incentives that will spur the rapid adoption of novel gene-edited technologies.

GENE EDITING: A PRIMER

The explosion of interest in gene editing expressed by the boom in scientific publications reflects the extraordinary flexibility and power of this new technology. Gene editing is already pushing beyond the lab, ushering in dramatic innovations in medicine and manufacturing as well as agriculture. The fight against COVID-19 will accelerate this trajectory, as gene editing is contributing to the development of antiviral therapies and vaccines.[4] It is, in short, a new platform technology that will touch many aspects of 21st century society, including climate and energy.

Gene editing allows the instructions guiding metabolism—the biochemistry of living things—to be tailored with precision. The term encompasses several different techniques, including zinc finger nucleases, transcription activator-like effector nucleases (TALENS), and meganucleases, but most attention is focused on CRISPR.[5] The acronym stands for “clustered regularly interspersed short palindromic repeats,” a label that describes what its DNA sequence looks like without illuminating where it came from or how it works.

CRISPR is an ancient defense mechanism bacteria evolved to protect themselves against viruses. Most CRISPR tools consist of a compound molecule with two main parts: a protein enzyme (called an endonuclease) that will cut or break genetic material (DNA or RNA) at a specific location, and a guide sequence made up of nucleotide bases that specifies precisely where in the target genome the cut will be executed.

A CRISPR guide sequence is a random fragment of a viral gene picked up by the ancestors of the bacterium during a viral infection they survived at some point in the past. Bacteria collect such random fragments of genes from attacking viruses and incorporate them into their own genomes as a kind of post office wall covered with “Most Wanted” mugshots. When the guide sequence detects an invading viral gene, the CRISPR endonuclease cleaves it, thereby disabling the invader. Guide sequences collected by the bacterium that have protected it against viral attacks are passed down to its descendants.

Gene editors can now add a DNA sequence they have designed to a genome at any location they choose by creating new guide sequences. They deploy these customized guide sequences with a CRISPR enzyme borrowed from a bacterium in order to cut the target genome at a precise location. The cells’ natural damage repair mechanisms then take over and reattach the severed DNA strands in a way that incorporates the new sequence at that location. The process is analogous to using a word-processing program to edit a document.[6]

CRISPR thus allows researchers routinely to make precise changes at any one of tens of millions of potential sites in an organism’s genome. Such edits can shut down the expression of a gene (called a “knockout”) or dial the expression up to a higher level; confer (or disarm) resistance to a disease, pest, or herbicide; increase (or decrease) the amount of specific nutrients in the food derived from the gene-edited plant or animal; and more. It is also becoming easier to use

CRISPR to import an entire new gene into a genome, which more precisely does what conventional genetic engineering methods have done for the last three decades.

Combined with the ability rapidly to sequence entire genomes, and tease out the role of specific genes and how they interact with others, CRISPR is making it possible to manipulate complex traits governed by hundreds of genes working in concert, such as water metabolism in plants. Until recently, such complex characteristics had been difficult or impossible to work with. This revolutionary technical capability has generated great excitement and hope. Among many other applications, gene editing promises to deliver numerous novel approaches to GHG mitigation and carbon removal.

GENE-EDITED SOLUTIONS FOR GHG EMISSIONS FROM AGRICULTURE

Agricultural GHG emissions arise from fuel, fertilizer, and other inputs—and also from agricultural waste. The growth of crops, on the other hand, pulls carbon from the air. Gene editing has the potential to impact each of these areas.

Impacts of Conventional Genetic Engineering in Agriculture

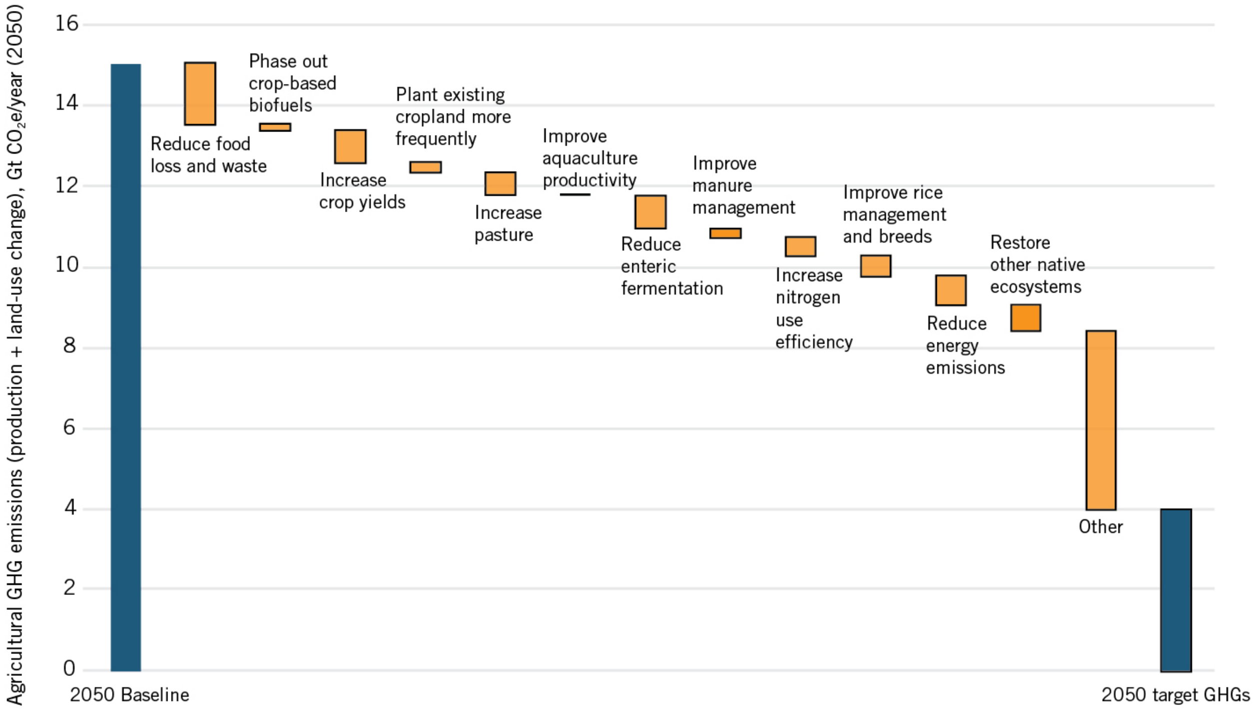
Conventional genetic engineering has already led to major, widespread increases in crop yields. The global gain from 1996 to 2016 averaged about 14 percent for maize and 15 percent for cotton.[7] One analysis of these developments finds *"significant net economic benefits at the farm level amounting to $17.7 billion in 2014 and $150.3 billion for the 19-year period 1996–2014 … The technology has … added 158 million tonnes and 322 million tonnes respectively, to the global production of soybeans and maize since the introduction of the technology in the mid-1990s."*[8]

*A global meta-analysis finds, "*On average, [genetic modification] technology adoption has reduced chemical pesticide use by 37 percent, increased crop yields by 22 percent, and increased farmer profits by 68 percent."[9] These results are corroborated by the economic ballots farmers cast for biotechnology-improved seeds wherever governments allow them to be sold.[10]

Gene Editing Applications: A Roadmap

Given the relative ease with which changes can be effected with gene editing, it is certain the technology will be used further to enhance crop traits in ways that will improve yields through insect and disease resistance, better weed control, and more. The World Resources Institute has developed a roadmap (figure 1) that spotlights the opportunities for emissions reductions in agriculture using gene editing.[11]

Figure 1: World Resources Institute roadmap to emissions-reduction opportunities[12]



Created by ITIF with data provided by World Resources Institute

Food waste reduction is obviously a candidate and is featured in the next section.[13] Crop-based biofuels production could certainly be made more efficient through gene editing. Increasing crop yields, planting croplands more frequently, and increasing pasture productivity all provide candidates for gene-edited improvements, as does increasing aquacultural productivity. Reducing enteric fermentation and improving manure management are related, and though their emissions are frequently overstated, they are nevertheless significant and ripe for gene-edited solutions. Finally, gene editing could clearly contribute to reforestation in multiple ways.

Reducing Food Loss and Waste

The United Nations Food and Agriculture Organization estimated that as much as one-third of the food grown around the world is wasted.[14] The decomposition of wasted food, and the fossil fuels used to produce and ship it, make up the single-largest component of agricultural GHG emissions, as much as 1.9 billion tons of carbon dioxide (CO_2) equivalent warming potential (gigatonnes (Gt) CO_2e) per year.[15] Several gene-edited innovations targeting these emissions are far advanced, and more are close to reaching the market.

The first gene-edited food product to reach the market was Calyno™ High Oleic Soybean Oil for food service applications. It was created by the biotech start-up Calyxt to be more heart healthy, approximating the nutritional attributes of olive oil.[16] Subsequent iterations of this product are certain to be further enhanced in ways that reduce its carbon footprint. For instance, a new version that lasts for three weeks could reduce food waste, costs, and associated GHG emissions by about two-thirds, because most oils used for deep frying last only one week.

Potatoes are another opportunity. In North America alone, an estimated 400 million pounds of potatoes are discarded annually due to bruising. J.R. Simplot is marketing potatoes genetically engineered to resist bruising, and thus produce less waste. The company recently negotiated a deal with Corteva for a license to use gene editing to introduce useful traits into crops more efficiently than current techniques.[17]

A surprising amount of food waste arises from browning. Academic researchers have used gene-editing "knockouts" to produce mushrooms that resist browning when cut. This technique is in principle easily transferable to many other fruits and vegetables. A non-browning apple known as the Arctic® Apple from Okanagan Specialty foods is already on the market.[18]

Plant diseases are a major cause of food waste. Fire blight, for instance, is a bacterial plague on apples and as many as 75 other fruits and vegetables. It is expensive to control and imposes substantial losses on farmers and food processors.[19] Gene editing offers multiple potential solutions to this disease and others.[20]

Insect damage also causes billions in food waste every year. These losses have been dramatically reduced thanks to conventional genetically engineering, particularly in corn and cotton.[21] Myriad additional gene-edited innovations to reduce food waste are possible to imagine, and many are being actively pursued by a variety of researchers.[22]

Increasing Crop Yields Through Improved Weed Control

Increased crop yields, such as reduced waste, allow farmers to produce more usable output without proportionately increasing inputs. The major obstacle to higher yields comes from weeds, though pests, diseases, and drought are also important. The use of gene editing to inhibit weeds would lead to considerable reductions in GHG emissions per unit harvested.

Tillage—or plowing—has been the preferred approach to weed control for centuries.[23] But the same disturbance of soil structure from tillage that impedes the growth of weeds is hugely disruptive to the microbial populations that are essential to soil health and responsible for much soil carbon sequestration. Tillage increases GHG emissions by accelerating microbial degradation of soil organic matter, while at the same time increasing water loss, and exacerbating erosion, which increases groundwater contamination and downstream pollution.

While it has become routine to make crops herbicide-tolerant using older genetic-engineering techniques, gene editing will make it even easier.

No practice has done more to improve soil health in agricultural lands than the adoption of no-till measures for weed control.[24] Genetically engineered herbicide-tolerant (HT) crops help facilitate adoption of this practice. Indeed, HT crops have proven so superior to other weed-control measures that they now comprise substantial majorities of the corn, cotton, and soybean crops in the United States, with similarly high rates of market penetration in virtually every country wherein governments allow them to be grown.[25]

Agricultural economists have documented reductions in GHG emissions due to reduced inputs, particularly fuel, from no-till farming.[26] The evidence on sequestration of GHG in soil is less clear-cut.[27] The EU has nevertheless set a target of applying no-till cultivation to 20 percent of European agricultural land, almost 20 million hectares.[28] One study found that if 50 percent of

European farmers adopted no-till weed control,“ 0.4 percent of all anthropogenic CO_2 emissions [0.2Gt CO_2 e] could be offset.”[29] The irony that draconian “precautionary” regulation in the EU is the leading global impediment to genetic innovations in agriculture is worth noting here.[30]

While it has become routine to make crops herbicide tolerant using older genetic engineering techniques, gene editing will make it even easier. Moreover, while older techniques have been hobbled by inappropriate and unscientific regulation, the products of gene editing are subject to far less onerous regulation in some jurisdictions.[31]

Several of the most serious weed pests today (like Palmer Amaranth) can be controlled only by herbicides with high impact and toxicity (like dicamba).[32] Gene editing can make such crops tolerant to less harmful herbicides. Each crop-herbicide pair represents a distinct opportunity and challenge, as herbicides act on plants in varying ways. But every step in the pathways through which an herbicide disrupts a plant’s metabolism and growth is an opportunity for gene editors to explore.[33]

While the difficulty of identifying new herbicidal active ingredients and modes of action remains considerable, the relative ease with which gene editing can be used to impart tolerance will dramatically expand the opportunity set. These new tools will not only help farmers manage weeds, the most important challenge they face in growing our food, they will simultaneously help them reduce GHG emissions as well through reduced fuel use and improved soil health.[34]

Raising Aquaculture Productivity

The need for more-productive aquaculture has never been more glaring. All the major wild fisheries on the planet are being harvested at or beyond sustainable levels.[35] Unfortunately, some aquaculture operations, such as shrimp-farming operations that depend on the destruction of mangrove forests, exacerbate climate change (and have other deleterious environmental impacts as well).[36] Closed systems that use recirculating, filtered water reduce aquaculture’s reliance on vulnerable natural resources. Raising fish such as salmon in such facilities, for instance, dramatically reduces such negative impacts as concentrated waste and disease transmission to wild fish.[37]

AquaBounty Technologies has made use of conventional genetic engineering to improve the economic viability of closed aquacultural systems. Scientists inserted regulatory genes from another ocean fish into Atlantic salmon, producing a new strain that will feed and grow throughout the year and reach market size in half the time of conventional farmed salmon (and on 20 percent less feed). (See figure 2.) The approach improves the economics of closed-circuit rearing enough to allow production facilities to be located close to major markets. That shift cuts emissions from shipping dramatically and reduces spoilage. The firm has already brought a product to market in Canada, and expects a late-2020 launch in the United States after years of regulatory delay and political obstruction.[38]

Figure 2: Salmon raised in closed-circuit facility

Photo courtesy of AquaBounty Technologies, Inc.

Now that this approach has been proven with salmon, gene editing promises to bring it within reach for more widely farmed fish such as tilapia and catfish, which could be made more disease resistant or faster growing.[39] Such advances could make the goal of dramatically increasing aquaculture production over the next several decades, which has been adopted by the United Nations' Food and Agriculture Organization, entirely realistic. The GHG mitigation benefits would be large.

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Moving shrimp farming to closed-circuit systems is an even more exciting prospect. The climate change mitigation benefits of slowing destruction of mangrove forests—one of the largest GHG sinks on Earth—would be significant. While there are indications that shrimp aquaculture is moving in this direction, it must be noted that the genetics of shrimp have been difficult to improve with conventional breeding techniques. Newer methods, such as genomic analysis and marker-assisted breeding, have begun to enable rapid progress, and gene editing may well accelerate that advance.[40]

Aquaculture is a far more efficient means of producing animal protein than most terrestrial animal husbandry.[41] The World Resources Institute (WRI) estimated in 2010 that global GHG emissions from aquaculture totaled 0.332 Gt CO_2e.[42] Genetic engineering has already delivered improvements in production efficiency in excess of 50 percent. As gene editing is brought into play and expanded to more species, such gains will be extended.

Reducing Ruminant Emissions

The world's 1.4 billion cattle comprise the second largest source of agricultural GHG emissions (after food waste). Estimates range as high as 14.5 percent of all global emissions if land use parameters are included. A more reasonable figure of 5.8 percent amounts to 2.86 Gt CO_2e per year, well above the estimated contributions of soils (4.1 percent) and rice cultivation (1.3 percent).[43]

Ruminant GHG eructations have been the subject of much heated discussion in recent years. The highly controversial and severely flawed EAT-Lancet report that proposed drastic reductions in meat consumption misrepresents the science and proposed proposes a diet that could lead to significant malnutrition.[44] But confusion over simplistic and flawed proposals should not lead us to set aside the topic. Ruminant GHG emissions are largely methane, a much more potent GHG than CO_2 (estimates range from 86 times as powerful, if measured over 20 years, to 28 times, if measured over 100 years).[45]

The global methane budget is complex, and the chemistry of ruminant GHG emissions and climate impacts is marked by some unusual twists.[46] Ruminant methane is caused mainly by symbiotic microbes in the digestive tract rather than the cattle themselves. The chemistry of methane in the atmosphere is such that once a cattle herd is established, its emissions will accrue for approximately 10 years. Beyond that, the rate of new methane production comes into equilibrium with the rate of atmospheric degradation.[47] Therefore, one particularly powerful and rapid means of decreasing ruminant methane emissions is reducing the size of cattle herds.

Each cow produces between 70 and 120 kilograms (kg) of methane a year.[48] In 1970, the total U.S. cattle population numbered 140 million head. Thanks to conventional genetic improvements through livestock breeding and improved nutrition, that figure had dropped to about 90 million by 2018, cutting methane emissions by approximately 11 million tons. Yet even with 50 million fewer cattle, the total domestic production of meat and dairy products has increased.[49]

Altering the diet of cattle could also cut methane emissions. Adding certain types of seaweed to cattle feed, for instance, has been shown to reduce methane emissions by as much as 67 percent. Such a diet changes the balance of microbes in the upper digestive tract, which are the main source of emissions.[50] Several companies have begun producing commercial feed additives of this type that could be on the market within a few years.[51] There are tradeoffs—CO_2 emissions may increase as methane emissions decline—but the approach shows promise. Other methods seek to capture methane emissions as a fuel source, rather than trying to eliminate them.[52]

A more enduring solution might come through gene editing combined with selective breeding. In an important study, Australian researchers examined 1,016 cattle in several herds, and found more than 250,000 different microbes in their digestive systems. A core group of 512 species was common among the herds, and a subset of 39 correlated with both productivity and methane generation. The presence of these species was heavily influenced by the cows' genetics.[53]

Figure 3: Dairy cows—a major source of methane emissions[54]

As the individual genes responsible for the presence of these microbes are identified, it will become straightforward to use gene editing to knock out those most responsible for high-methane production bacteria or increase the expression of others that favor low-methane species. The findings of this study were so striking that the authors proposed "microbiome-led breeding/genetic programs to provide a sustainable solution to increase efficiency and lower emissions from ruminant livestock."[55] Researchers in New Zealand are following similar paths and seek to extend gene-editing techniques to sheep as well as cattle.[56]

Improving Nitrogen-Use Efficiency

Nitrogen is the second-most important rate-limiting input in agriculture after water. Farmers use some 500 million metric tons of this element in fertilizer each year to grow the world's three most important food crops: rice, maize, and wheat. The efficiency with which crops take up and use nitrogen is therefore an obvious target for improvement. Because fertilizer is an important source of GHGs, such advances hold great potential for mitigation, perhaps by as much as 0.7 Gt CO_2e per year by 2030.[57] A more narrowly framed estimate by WRI predicts that gene editing and other breakthrough technologies for improving nitrogen use efficiency (NUE) would reduce 2050 emissions by 0.5 Gt CO_2e.[58]

However, the genetics of the multiple metabolic pathways involved in NUE are not well-understood. Scientists are not yet able to identify specific targets for gene editing. Still, a recent review finds *"a promising potential of genetic transformations approaches for improving certain NUE parameters."*[59] *It follows, therefore, that the potential for gene-edited improvements to cut emissions exists and may well be substantial. Further research will be required to clarify its potential.*

Reducing Methane Emissions From Rice Paddies

WRI estimated annual global emissions of methane from rice cultivation to be about 1.3 percent of global emissions, equivalent to 0.6 Gt CO_2e. [60] Rice is the staple crop for more than half the world's population, and 90 percent of it is consumed within 100 miles of where it is grown.[61] Reducing emissions from rice cultivation is complicated by this highly distributed pattern of cultivation. Rice farming's emissions originate with anaerobic bacteria in the soil. When rice fields are flooded, as they are during much of the growing season in many parts of the world, these microbes generate methane. Although 60 to 90 percent of such methane never reaches the atmosphere, the remaining portion still presents a problem that can be remediated.[62]

Researchers are pursuing genetic methods to alter rice to this end, and such efforts will no doubt be enhanced by gene editing tools.[63] The aspects of water metabolism that dictate rice's affinity for flood irrigation are all under genetic control, and research is yielding significant insights into them.[64] In addition, the production of root exudates, which drive much methane production, varies among cultivars.[65] As the genetics regulating these processes become better understood, new opportunities for gene editing will emerge.

It is virtually certain that in the near future there will be multiple possible avenues to reduce methane generation from rice production.[66] Manipulations of the soil microbes in rice paddies have already shown efficacy, and gene editing could be used to make further gains.[67] As this work progresses, though, unintended consequences must be considered. For instance, flooded rice fields play a major role as habitat for migratory waterfowl, including a number of endangered species.[68]

GENE-EDITED SOLUTIONS FOR NONAGRICULTURAL GHG EMISSIONS AND CARBON REMOVAL

While reducing agricultural emissions is the most obvious application of gene editing, these techniques may also be used to cut emissions in other sectors. GHG emissions related to transportation, electricity and heat, buildings, and manufacturing and construction make up a large majority of global GHG emissions. Although most of the activities that drive these emissions are abiotic, biological tools will nonetheless create options worth pursuing.

Biofuels

If fuels can be grown, rather than extracted from the earth, the crops that make them become temporary carbon sinks. If these crops can be grown with minimal carbon inputs (such as fertilizer made with zero-carbon electricity), the fuel system could become carbon-neutral. Gene-editing tools might be applied to create highly productive fuel crops.

The first big push into biofuels was the manufacture of ethanol from corn, which now consumes approximately one third of the U.S. corn harvest (5.6 out of 14.6 M bushels in 2018).[69] A 1998 study predicted that corn ethanol "could provide one third of the carbon reductions needed to stabilize carbon emissions from personal vehicles in 2020."[70] But first-generation biofuels have not been the environmental boon such advocates anticipated.[71] WRI calculated, "Current bioenergy strategies, if fully realized, could require harvesting levels of biomass equal to all the world's presently harvested crops, crop residues, wood, and forages consumed by livestock." Rather than simply raising yields and incrementally improving efficiency, breakthroughs that change the paradigm are needed.[72]

The main impediment to making biofuels economically competitive is cellulose, a complex carbohydrate that comprises a major portion of plant biomass and requires a lot of energy to break down. Ruminants and termites break down cellulose by harnessing symbiotic microbes, but humans have not yet been able to replicate this feat at scale despite considerable effort.[73] Researchers are using breeding and genomic analysis—an effort that could be accelerated with gene editing—to solve this puzzle.[74] Some have recently begun to apply CRISPR tools, "redesigning of [*sic*] microbes for higher product concentration, enhanced inhibitor tolerance, modifying cellulases and hemicellulases, improved product yield, and product tolerance." Advances in any, much less several, of these areas could bring considerable benefits.[75] Switchgrass, sorghum, and even trees may become economical source materials for biofuels if cellulosic biomass processing can be made more efficient.[76]

Figure 4: Switchgrass: a potential biofuel crop[77]

A different approach involves harnessing algae to produce energy-dense compounds, such as butanol, that have potentially wide utility to replace fossil fuel.[78] The considerable potential for gene-edited improvements in this process is just beginning to be explored, and expanded progress would be accelerated by increased R&D support into understanding the metabolism and genetics of algae.[79]

Algal Carbon Capture, Utilization, and Storage

Most modeling of the transition to global net-zero emissions by 2050 suggests carbon capture will have to be deployed on a significant scale. Carbon capture can perform two significant duties: reducing or eliminating emissions from point sources such as power plants, and pulling carbon out of the air to reduce the atmospheric GHG reservoir. Point sources produce much more-concentrated streams of GHGs and are therefore the most immediate targets for gene-edited solutions. Sustained growth of carbon capture at double the current rate would yield 1 Gt of emissions per year by 2040.[80]

In addition to capturing CO_2, algae have the potential to produce high-value products that utilize captured carbon, such as fuels and specialty chemicals. These products could help make the technology economically competitive in a wide range of applications in the power and industry sectors.[81] Gene editing could be helpful in tailoring algae to more efficiently fix CO_2 through approaches such as those being used to improve photosynthetic efficiency in terrestrial crops. It may also be helpful in enhancing algal capabilities to deal with heavy metals, which frequently contaminate power and industrial-waste streams. There is a long history of plants evolving tolerance to such compounds, and it is highly likely elements of the plant biochemistry involved would be transferable.[82]

The main challenge for algal carbon capture, utilization, and storage (CCUS) is the need for substantial land area for ponds and raceways. (Bioreactors would be vastly more costly and likely uneconomical except for high-value applications.) Conversion for this purpose of land that currently serves as a carbon sink—such as swamps, grasslands, and forests—could outweigh the gains. While the knowledge required to bring algal CCUS to maturity is far from complete, clearly the technology has significant potential—and pilot studies look promising.[83]

Increasing Carbon Sequestration

Carbon sinks are critical to meet the climate challenge. In 2004, one researcher estimated that "carbon sequestration [by natural sinks] has the potential to offset fossil fuel emissions by … 5 to 15 percent of the global fossil-fuel emissions" annually.[84] The U.S. National Academy of Sciences found that sequestering carbon in soils could provide a low-cost solution to offset as much as 10 percent of total U.S. emissions.[85] Gene editing could enhance carbon sequestration in many ways, but at the most basic level, they all depend on photosynthesis, which is the source of all life on earth.[86]

Improving Photosynthesis

Photosynthesis is the process through which plants use energy provided by light to transform atmospheric CO_2 and water into carbohydrates and oxygen. Photosynthesis is (in the words of the Salk Institute) "the most elegant and efficient tool at our disposal to reduce the levels of atmospheric CO_2. Nature is our best ally in solving the climate crisis because it already functions as a 'negative emission technology,' requiring only our help to super-charge the process through scientific innovation."[87]

While the maximum theoretical efficiency of photosynthesis is about 12 percent, most plants harness only 1–2 percent of the light that lands on them. Improving the efficiency of photosynthesis will help reduce emissions and could make carbon removal from the atmosphere economical.[88] An effective photosynthesis hack would deliver a powerful platform technology with broad utility in a variety of applications.

Plant photosynthesis can be broken down into two general types known as C3 and C4, so named for the number of carbon atoms in the molecules they make out of atmospheric CO_2. Both types involve multiple linked biochemical pathways offering numerous options for gene-edited interventions. Most plants use C3 photosynthesis, but C4 is more efficient. Conferring some of the efficiency advantages from C4 plants to C3 plants is a major focus of research.

One approach focuses on a single molecule, an enzyme called rubisco (abbreviated from ribulose-1,5-bisphosphate carboxylase/oxygenase) which is of central importance to photosynthesis. As one scholar put it, "Our ability to remove CO_2 from the air is entirely dependent on the inefficient mechanism of rubisco, the world's most abundant enzyme."[89] Studying rubisco has become a high priority for the research community, and a portion of that energy is focused on engineering the enzyme to make it more efficient.[90]

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Another innovative approach (which has attracted some mainstream media attention in recent years) builds on a defense mechanism that some plants evolved to protect against too much sunlight.[91] To avoid the accumulation of excessive heat, such plants are able to shut down their photosynthetic machinery. Once high levels of sunlight have subsided, the plant reboots its photosynthetic processes. But this restoration is not immediate; there is sometimes a considerable lag. By shortening the response times of the genes managing this reboot, geneticists at the University of Illinois discovered they can increase a plant's overall photosynthetic output by as much as 20 percent.[92]

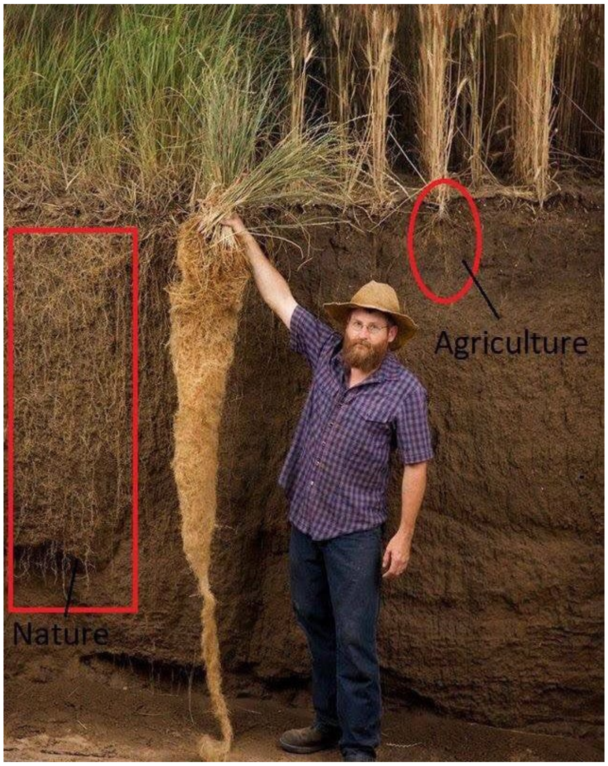
It remains to be seen whether this particular finding can be extended from the special conditions under which it has been demonstrated in tobacco to major crops such as corn, wheat, and rice.[93] But the research so far reported confirms abundant potential for improving photosynthetic efficiency through gene editing as well as conventional genetic engineering. Myriad other opportunities to intervene in photosynthetic pathways are waiting to be tapped, and researchers estimate the potential gains in major crops may be as high as 50 percent.[94] This area is full of promise, and ready to absorb substantial increases in research support with a high potential for significant returns on investment.

Enhancing Root Growth

Enhancing plant-root growth to increase carbon sequestration is a promising possibility. As one writer put it, "[W]hat if we were able to help deepen the sinks—to work with nature, to lean into the curve, to help it help us out of a mess of our own making? Nature … is an amazing, complex, and remarkably effective technology—our biggest and most overlooked ally in the climate fight."[95]

One researcher found that "doubling the steady-state depth of roots from approx. 1 m to 2 m can have a significantly beneficial impact on lowering the levels of atmospheric CO_2."[96] In the United States, the potential for increased soil carbon sequestration could be as much as 100–500 million metric tonnes of CO_2/year. Reaching the upper limit would entail doubling the carbon content of crop roots, with their growth penetrating deeper, more closely to approximate the morphology of perennial grasses, as seen in figure 4.[97] Researchers have identified four major targets for exploitation: root architecture, root depth, perenniality, and low/no-till agriculture.

Figure 5: The difference between wild and cultivated crop root growth[98]



Several root-architecture traits are known to be under genetic control, including the length of the primary or main root, the nature and extent of root branching, and the formation and proliferation of the root hairs that provide the scaffolding for symbiotic fungi and microbes. But the chief of these is, of course, root depth. Most crop plants have roots that penetrate the earth to a depth of one meter or less. But many uncultivated or wild plants (especially trees and perennials) have roots extending two meters or more, suggesting that "there is considerable scope for increasing the depth of roots by appropriate breeding strategies."[99] Several research projects are extending the approach used by green revolution pioneer Norman Borlaug, by developing plants with more massive root systems.[100]

Perennial crops such as fruit and nut trees live longer than one year and are harvested repeatedly. Their root systems are more extensive, and penetrate deeper than those of annual crops, which enhances their value for carbon capture and sequestration. Recent research indicates perennializing annual crops may be worth exploring.[101] The genetics of these major traits, however, are not well understood, marking this as another area in need of more basic research.

The potential for increased root growth to increase soil carbon sequestration depends on the longevity in soils of the increased root biomass. In some temperate grasslands, the annual loss of root material through decay may be as high as 40 percent.[102] There is, however, a lack of data on this question, due primarily to the difficulty of measuring soil carbon, and the lack of baseline data.

Expanding root biomass for carbon sequestration will also require changes to agronomic practice. Carbon captured in roots can quickly find its way back into the atmosphere if, for example, tillage is resumed or land is withdrawn from conservation reserves and returned to annual crop production.[103] Increased root biomass could also reduce yields. Many challenging trade-offs must be resolved before this pathway provides significant benefits.[104]

Enhancing Trees as Carbon Sinks

Growing new trees and preserving old ones contributes to GHG reductions by maintaining natural sinks and avoiding the conversion of land to GHG-emitting end uses. "Trees build themselves from almost nothing, transforming sunlight, carbon dioxide, and water into millions of tons of biomass—approximately half of which is pure carbon, locked safely away from the atmosphere. And old trees, by virtue of their age and size, can hold far more carbon than anybody else.... this technology just works, year-round. It runs on solar power. It creates all of this from thin air."[105]

Figure 6: Sequoias, Yosemite National Park, California, United States[106]

Many forest ecosystems have been actively managed to optimize extracted value. This approach can easily be adapted to place a higher emphasis on carbon sequestration with the appropriate incentives.[107] "In the Northwest, Douglas fir plantations are commonly cut every 35 to 40 years.... letting trees live to 80 or 100, while potentially less lucrative, produces more wood and sequesters more carbon."[108] Older, more mature trees in climax forests sequester vastly more carbon than second-growth populations of younger trees.[109] In fact, "with targeted thinning and management, you can create old-growth features even in homogenous commercial forests, allowing space for trees to grow to huge sizes in the future." [110]

Gene editing could increase the carbon captured by trees in a number of ways. Although the availability of nutrients and water are clear limiting factors, the growth and metabolism of trees are all under genetic control. Growth rates; root, trunk, branch and canopy morphology and mass; metabolic activity; and disease and pest susceptibility are all mediated by panoplies of enzymes encoded by genes that might be edited. Trees have already been developed through conventional genetic engineering, with dramatically increased growth rates and altered chemical composition, to make them easier to use in paper processing, construction, and other industries.[111] There is no doubt gene editing will expand and make much easier to achieve the range of improvements one can imagine.

Gene editing could increase the carbon captured by trees in a number of ways.

The prospect of forest plantations consisting entirely of trees with accelerated growth rates and tailored structural characteristics to increase their value as building material, paper stock, or other products is now entirely achievable. Indeed, it is being actively pursued by multiple players on several continents.[112] It must not be forgotten, however, that producing arboreal biomass at scale will require not only land area but water and fertilizer as well. These demands may have extended ripple effects that must be factored into cost-benefit analyses.

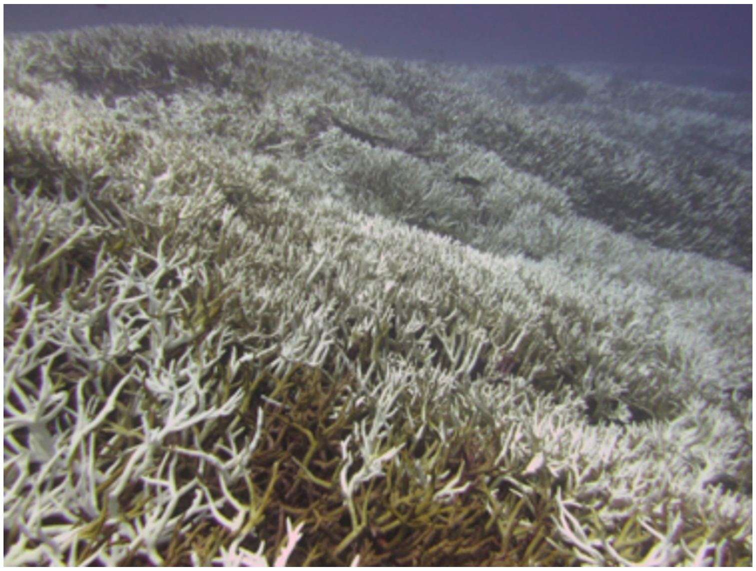
Protecting and Restoring Natural Ecosystems

Preventing existing natural carbon reservoirs—forests, grasslands, peatlands, marshes, mangroves, and sea grasses—from being degraded is an obvious priority for climate policy.[113] Gene-edited solutions could help. The technical complexity and uncertainties in understanding and measurement make it impossible to venture a rigorous estimate of GHG reduction potential in this area.[114] But there are countless ways in which gene editing might be used to enhance the survivability of species facing disease, or competition with invasive species that threaten ecosystems, that are important carbon sinks.[115]

For instance, threats to native forests can be reduced by improving the productivity of forest plantations as well as the crops for which forests are presently being destroyed, such as oil palm in southeast Asia, and cattle and soybeans in Brazil. Increasing agricultural productivity generally decreases pressure on natural ecosystems, and gene editing is well on the road to accelerating such developments.[116]

Oceanic biota are threatened not only by elevated temperatures but also by increased levels of dissolved CO_2, which have increased ocean acidity by 30 percent since the dawn of the industrial revolution.[117] These trends pose a particular threat to corals, stressing and killing the tiny animals that create reefs. Once uncommon, the resulting phenomenon, known as bleaching, has increased dramatically over the past few decades, with most of the major coral reef populations in the world showing signs of considerable stress.[118] A number of research teams are exploring ways to increase the resilience of corals to such insults, including some that involve gene editing.[119]

Figure 7: Coral bleaching in the Pacific Ocean[120]



Geoengineering is a nascent discipline devoted to planetary-scale modifications of nutrient cycles or energy flows to achieve specific ends. Some have proposed increasing carbon sequestration in the deep sea by triggering algae blooms through oversupplying rate-limiting nutrients such as iron.[121] Although preliminary field trials have given positive results, it is clear the process is more complicated than initially thought.[122] Even so, the growth rates of marine algae are under genetic control, and increased understanding of their metabolic processes would be certain to illuminate potential targets for gene-edited interventions.

It is one thing to achieve progress in the lab, and quite another to transfer that progress at scale to complex ecosystems. A lively debate is underway with regard to whether seeking to impact natural ecosystem services, such as carbon sequestration, would be prudent, or perhaps even ethical.[123] While these conversations should not be short-circuited, researchers must forge ahead to discover opportunities and provide evidence to inform public policy.

RECOMMENDATIONS

Several classes of actions would speed the delivery of climate benefits from gene-edited solutions. In the near and medium term, no other action will produce quicker positive results than regulatory reform. Over the longer term, increased public investment in R&D, especially basic research, would have a substantial impact. Improved national and international coordination of public R&D should also play a major role. As solutions are developed, a global effort will be needed to effectively implement them, which will require deployment incentives across all sectors.

Regulatory Reform

Outdated, unscientific regulations are slowing the pace and raising the cost of innovations based on biotechnology, including gene editing, without enhancing safety. There is no single policy change that would have a greater impact on the pace of progress than regulatory reform. Around the world, including in the United States, regulatory hurdles for innovative crops bred to resist insect pests or diseases through traditional breeding methods are minimal or nonexistent, while those developed using modern tools must navigate a long series of obstacles without any added health or safety benefits.[124] With few exceptions, every gene-edited innovation described in this report would face extensive regulatory delays that would add years to the timeline and millions of dollars in costs to their development. Regulation is an enormous disincentive to innovation in this field.[125]

Extensive evidence confirms that these innovations are safe. The U.S. Centers for Disease Control have not recorded a single human death caused by a new crop variety, nor has the U.S. Department of Agriculture (USDA) or Environmental Protection Agency (EPA) discovered anything but positive environmental impacts from growing such crop varieties.[126] Scientists and risk management experts have long argued for regulations based on actual risks. Yet governments around the world continue to regulate these innovations primarily on the basis of the process through which they were derived, rather than the traits through which any risk would be manifested.

Among the major economies, the European Union's regulatory regime is the most counterproductive.[127] European scientists, galvanized by a blinkered 2018 ruling from the EU Court of Justice, have argued compellingly for a more rational, science-based regulatory approach.[128] While the United States' approach is better, and the Trump administration has moved it forward in recent years, there is still substantial room for improvement.[129] For instance, USDA has announced new policies that simplify or waive regulations of some agricultural products that have been genetically engineered or gene edited, but many improved varieties presenting no significant or novel hazards remain regulated.[130] Moreover, the U.S. Food and Drug Administration (FDA) and EPA, which also have major regulatory roles in this area, have yet to reform their rules in a comparable manner.[131]

Action Agenda:

- Governments around the world should eliminate unwarranted regulations inhibiting the development and deployment of gene-edited products with the potential to reduce GHG emissions.
- Regulators should review the experience with genetically engineered and gene-edited crops to date and update their policies to reflect its results.

Increased R&D Investment

Biological research, particularly in agriculture, is one of the best investments governments can make.[132] A study of investment in agricultural R&D by the U.S. government between 1953 and 2015 finds a 12-fold return, which is more than sufficient to justify a considerable increase from today's baseline. For one mitigation option—enhancing crop root systems to sequester more carbon— alone, the U.S. National Academies of Sciences recently recommended a 400–500 percent increase in funding over current levels for at least 20 years.[133]

Priorities for R&D funding include:

- how CRISPR works in nature, in the laboratory, and in practice;
- photosynthesis;
- the genetics of root architecture and growth in crops, including trees;

- methods for measuring soil carbon content and surveys to collect reliable baseline data from multiple ecosystems and conditions;[134]
- livestock breeding and improved management of ruminant microbiomes; and
- microbial and algal systems for CCUS in powerplants and industrial facilities.

Photosynthesis deserves special emphasis. If researchers can gain a detailed understanding of the genetics underlying the enzymatic pathways involved in photosynthesis, and the phenological changes these pathways regulate in plants, they will be able to develop tools to increase the efficiency of this ubiquitous process. These tools will unlock GHG mitigation opportunities through many channels.[135]

Action Agenda:

- Governments should increase several-fold investment in R&D for gene-edited solutions for climate change, especially in the priority areas previously listed. Current R&D funding levels are not commensurate with the challenges and opportunities in these fields.
- The U.S. Department of Energy (DOE) should expand its recent initiative to support research into artificial photosynthesis.[136] Other governments should begin similar programs.
- The U.S. Congress and the president should establish a new agricultural research organization in the mold of the Defense Advanced Research Projects Agency (DARPA) or Advanced Research Projects Agency–Energy (ARPA-E), as Senator Michael Bennet has proposed. The ARPA model, which features rotating program managers recruited with commercially-competitive hiring authorities, has proven highly successful for driving high-risk, high-reward research programs.[137]

Improved Coordination of R&D Policies

In addition to increasing R&D investment in gene-edited solutions for climate change, strengthening coordination of the management of that investment within and between governments would further accelerate progress. Existing international research efforts can serve as starting points for multilateral coordination. One example is the Realizing Increased Photosynthetic Efficiency (RIPE) Project, started in 2012 by the Bill and Melinda Gates Foundation, and joined later by USDA's Foundation for Food and Agriculture Research (FFAR) and the U.K. Department for International Development. Within the United States, an array of agencies and laboratories, including the DOE Bioenergy Technologies Office, National Institute of Health's National Institute of General Medical Sciences, USDA Economic Research Service and Animal and Plant Health Inspection Service, EPA, and FDA, all have important roles to play in moving gene-edited climate solutions forward.

Action Agenda:

- Nations that make significant investments in gene-editing R&D should work with the RIPE project to create a worldwide climate-solutions initiative in collaboration with philanthropic and industrial partners.
- The White House Office of Science and Technology Policy (OSTP) should develop and oversee a national strategy. OSTP's 2019 Bioeconomy Initiative provides a good initial building block.[138]

Incentives to Encourage Deployment of Gene-Edited Technologies

The importance of strong governmental support for basic research is unsurpassed, and the high returns on such investments are well documented over many decades.[139] But without effective incentives to drive deployment of innovations arising from R&D—especially early adoption—and reduce their costs over time, farmers and other stakeholders are unlikely to put gene-edited climate solutions to use.

Action Agenda:

- Governments should support technology demonstrations and other approaches to build confidence among stakeholders.
- Governments should take into account the social and environmental benefits of reducing or capturing GHG emissions by offering incentives that reward farmers for adopting climate solutions such as crops with enhanced root growth or rice with lower methane emissions.
- Existing conservation programs around the world, including tax incentives, should be expanded and tailored to enhance carbon sequestration.
- In the United States, Congress should expand programs such as the Soil Health Demonstration Trials, which were authorized in the 2018 Farm Bill, and provide grants to producers to test innovative approaches to improve soil health.[140] Congress should also expand support for outreach and extension staff at key federal agencies.
- Congress should allow farmers, state and local governments, and other land stewards to benefit from the Section 45Q tax credit for carbon capture projects that employ nascent gene-edited technologies.[141]

RESPONDING TO CONCERNS

Some argue that gene editing—whether applied to climate change or for any other purpose—should be out of bounds because such human "meddling" with the "natural" world is dangerous, unpredictable, and "unnatural."[142] Such arguments have been harshly criticized by scientists, and emphatically rejected by society. Farmers continue to plant, grow, and harvest the fruits of breeding innovations as they have done for tens of thousands of years.[143] Arguments about what is "natural" have fueled philosophical debate at least since Plato, and the debate will never end.[144] But it remains a fact, as noted earlier in this paper, that the techniques of genetic engineering, of which gene editing is a special case, are things humans learned how to do by discovering them in nature, where they have been operating without regulatory supervision for hundreds of millions of years. Any critique of them as "unnatural" must first overcome strong opposing testimony from nature itself.

Some argue we don't know enough about these techniques to be confident they can be safely used, that there may be hazards and risks with which we are unfamiliar that could usher in unacceptable harms. Thousands of years of plant breeding, and three decades of massive experience with crops and foods derived through biotechnology, negate such claims.[145] Despite 11 studies in the past 4 decades, the U.S. National Academies of Science have failed to detect even a hint of novel hazards associated with genetic engineering or gene editing—and other authoritative bodies around the world have reached similar findings.[146] Indeed, the only safety differential between products of genetic engineering so far discovered and those of older breeding methods indicate the former to be safer than the latter.[147]

To be sure, these technologies, like others, can be abused. The November 2018 announcement of an attempt to edit the genes of human embryos who were later born as baby girls provides a concrete example. But among the several lessons from this event, the most important is the near-universal opprobrium with which this misguided enterprise was greeted by the global scientific community. It ended the career of the researcher who foolishly undertook the effort.[148] The wide recognition of the attempt's impropriety demonstrates a level of societal attention and policing that will act as a check against similar misadventures in the future. Meanwhile, the benefits of gene editing in various spheres continue to roll out.[149]

CONCLUSIONS

Climate and clean energy innovation have been focused on physical and chemical solutions. It is time for biology to play a bigger role in solving one of humanity's greatest challenges. Innovations based on biological knowledge and techniques have had an extraordinary impact on food production over the past century. The eightfold increase in corn yields is but one example.[150] Similar gains have been made in soy, cotton, oilseeds, and fruits and vegetables—and in livestock management as well.[151] These gains have been due largely to improved agricultural practices in weed control, pest and disease management, and irrigation, but much has been attributable to genetic improvements.[152]

Based on the dramatic increases in agricultural productivity technological advances have wrought over the past century, gene editing could lead to a 50 percent improvement in agricultural productivity by 2050.

While it is difficult—perhaps impossible—quantitatively to estimate the extent to which gene-edited solutions can contribute to climate change mitigation, it is clear the potential is considerable. This toolkit is so powerful, its applications so widespread, and its development so rapid that we simply cannot yet conceive all the ways in which it will be used in the coming decades. We would hazard a guess, based on the dramatic increases in agricultural productivity technological advances have wrought over the past century, that gene editing could lead to a 50 percent improvement in agricultural productivity by 2050. That would translate into a commensurate reduction in agricultural GHG emissions while at the same time contributing to significant increases in carbon sequestration in other sectors. With sufficient support for and coordination of R&D, scientifically defensible regulatory policies, and incentives for private-sector deployment, there is ample basis to expect a significant positive contribution from gene-edited solutions to the challenges of climate change.

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