Sequestering carbon on a gigaton scale: How gene editing can address climate change by reducing atmospheric emissions

Hardly a day goes by without another piece praising the potential for gene editing to help solve climate change. Nevertheless, the possible contributions of biology and biotechnology have been conspicuously underplayed in most of the International Panel on Climate Change (IPCC) analyses. This is, perhaps, at least partly because it is no small thing to carry an idea from inception to delivery; to bridge the valley of death and deliver a functional solution to a specific problem. But this may be starting to change.

On February 7–8 a small group of researchers met at the U.S. National Academy of Sciences (NAS) in an informal (and partly hybrid) meeting entitled “How Can Agrigenomics Help to Address Climate Change?” The workshop featured speakers from around the world convened to discuss how best to demonstrate proof of concept for selected applications and start to flesh out plans to reduce them to practice at scale. Each of these concepts has the potential to remove gigatons of carbon from the atmosphere within the foreseeable future. Cutting emissions is important but reducing atmospheric carbon concentrations is essential. If we can’t figure out how to do that the fight is lost.

And, how to cut emissions and capture carbon in an arena that incentivizes sneaky usage?

Credit: Katie Louise Thomas

Even if humanity succeeds in eliminating carbon emissions altogether—difficult to do while keeping the population fed, housed, and clothed—there is still a large amount of carbon in the atmosphere beyond the capacity of earth's natural ecosystem processes to absorb. That excess amount is approximately 34 Gigatons—34,000,000,000 tons of carbon.

To bring the concentration of atmospheric carbon back into balance humanity must eliminate those emissions and reduce or eliminate the accumulated excess accrued over the past 200 years, some 200GT. To do that we need techniques that will deliver at scale—very large scale—and economically. With techniques like those described below, and many more, this is tractable. But to do so we need to do more than just innovate technologies; we need to remove obstacles to such innovations in policies, law, and regulation. It's time for countries around the world, including the United States, and especially the member states of the European Union, to set aside laws and regulations left over from the early days of the biotechnology revolution. These were driven by fears that have long been shown unfounded, and a lack of understanding now thoroughly remedied by experience and must be replaced by policies that will enhance and enable innovations rather than impede them. The world waits.

What follows is a summary narrative of a second meeting on biotechnological innovations for climate change solutions funded by the Bill & Melinda Gates Foundation. The first was held on November 11–12, 2021, at Boston University.

Individual speakers at the latest meeting described specific proposals summarized below and estimated the costs involved and the impact their application could have if it were deployed at scale. Each application has the potential to sequester carbon on the gigaton scale. It is important to note that each of these projects affords multiple opportunities to leverage impacts through synergies with the other projects described, and more. Table 1 highlights some of the projects speakers are pursuing.

Table 1: Project proposals presented February 7–8, 2022, at the informal workshop, "How Can Agrigenomics Help to Address Climate Change?"

Project	Institution	Lead
Adjusting stomatal density to reduce water requirements in rice	University of Sheffield	Julie Gray
Capturing agricultural methane emissions with methane eating bacteria	University of Washington	Mary Lidstrom
Blocking conversion of excess nitrogen fertilizers to GHG emissions by improving nitrogen use efficiency in crops	University of Alberta	Lisa Stein
Boosting photosynthetic efficiency by engineering better RuBisCO enzymes	Harvard	Pam Silver & Dan Davidi
Engineering microbes to sequester carbon by accelerating Silicate-carbonate weathering	Project Vesta	Ken Nealson
Reinventing photosynthesis	Max Planck Society	Tobias Erb
Engineering trees to grow faster/sequester more atmospheric carbon	Futuragene	
Engineering faster growing trees and grasses to sequester atmospheric carbon and reduce emissions	Oak Ridge National Lab	Xiaohan Yang

Credit: ITIF

Julie Gray, (University of Sheffield) described how rice is a major food crop, but its water intensive cultivation leads to greenhouse gas emissions estimated to account for 2.5 percent of human-induced climate change. This could be substantially alleviated by optimizing crops to reduce water loss and speed the much-needed shift from paddy rice towards dry seeded systems. In collaboration with the International Rice Research Institute in the Philippines, novel rice varieties with reduced stomatal density have already been produced through gene editing and trait selection that could be field tested rapidly and adopted by farmers within eight years. The combined impact of enhanced rice drought tolerance, together with reduced methane emissions and energy savings from irrigation could save over 1GtCO_2e (gigaton carbon dioxide emissions equivalent) emissions per year, with further reductions possible by application to other major food crops including maize, soybean, and rice as well as biomass crops like poplar and switchgrass.

Mary Lidstrom (University of Washington) described a plan for methane capture from air using aerobic methanotrophs. Methane has a warming impact 34 times greater than CO_2 on a 100-year timescale (86 times greater on a 20-year timescale) and a relatively short half-life in the atmosphere (~10 years). This makes it a key short-term target for slowing global warming by 2050. Lidstrom's team is developing biofilter technology using bacteria that metabolize methane, to remove methane from the air over emission sites, including agricultural areas, where methane is enriched compared to the atmosphere as a whole. This technology will be designed also to reduce production of another greenhouse gas, N_2O, by limiting nitrate availability. By targeting tens of thousands of such sites, enhancing the current capacity of such technology, and envisioning a 20-year deployment, it would be possible to remove a total of 0.3 Gt methane (10 Gt CO_2eq) by 2050 (0.5 Gt CO_2eq/yr), resulting in 0.2^{o}C less global warming.

Lisa Stein (University of Alberta) is working with biological nitrification inhibitors and soil-free systems. While the Haber-Bosch process for N-fixation has enabled a stable food supply for half of humanity, the heavy use of synthetic fertilizers has caused a radical imbalance in the global N-cycle. The resulting increases in nitrate production and GHG emissions have contributed to eutrophication of ground and surface waters, growth of oxygen depleted zones in coastal regions, ozone depletion and exacerbated rising global temperatures. According to the Food and Agriculture Organization of the United Nations, agriculture releases approximately 9.3 Gt CO_2 equivalents per year, of which methane and nitrous oxide account for 5.3 Gt CO_2 equivalents. N-pollution and slowing the runaway N-cycle requires a combined effort to replace chemical fertilizers with nitrification inhibitors based on biological formulations, which after a 10-year span of usage could eliminate at least 30 percent of ag-related GHG emissions (~1.59GT), protect waterways from nitrate pollution, and protect soils from further deterioration. Stein's team aims to bring biological nitrification inhibitors (BNIs) to the marketplace to curb the microbial conversion of fertilizer nitrogen into greenhouse gases and other toxic intermediates. Worldwide adoption of these plant derived BNI molecules in combination with biological fertilizers would substantially elevate nitrogen use efficiency by crops while blocking the dominant source of nitrous oxide to the atmosphere. In addition to biological fertilizers and BNIs, a second project to curtail N-pollution, soil erosion, and deterioration of freshwater supplies pursues the development of improved microbial inocula to increase nitrogen use efficiencywithout GHG production in soil-free hydro- and aquaponics operations. The carbon cycle in these systemscan be closed by including anaerobic digestion of solid waste followed by microbial conversion of methaneinto single cell protein for fish feed.

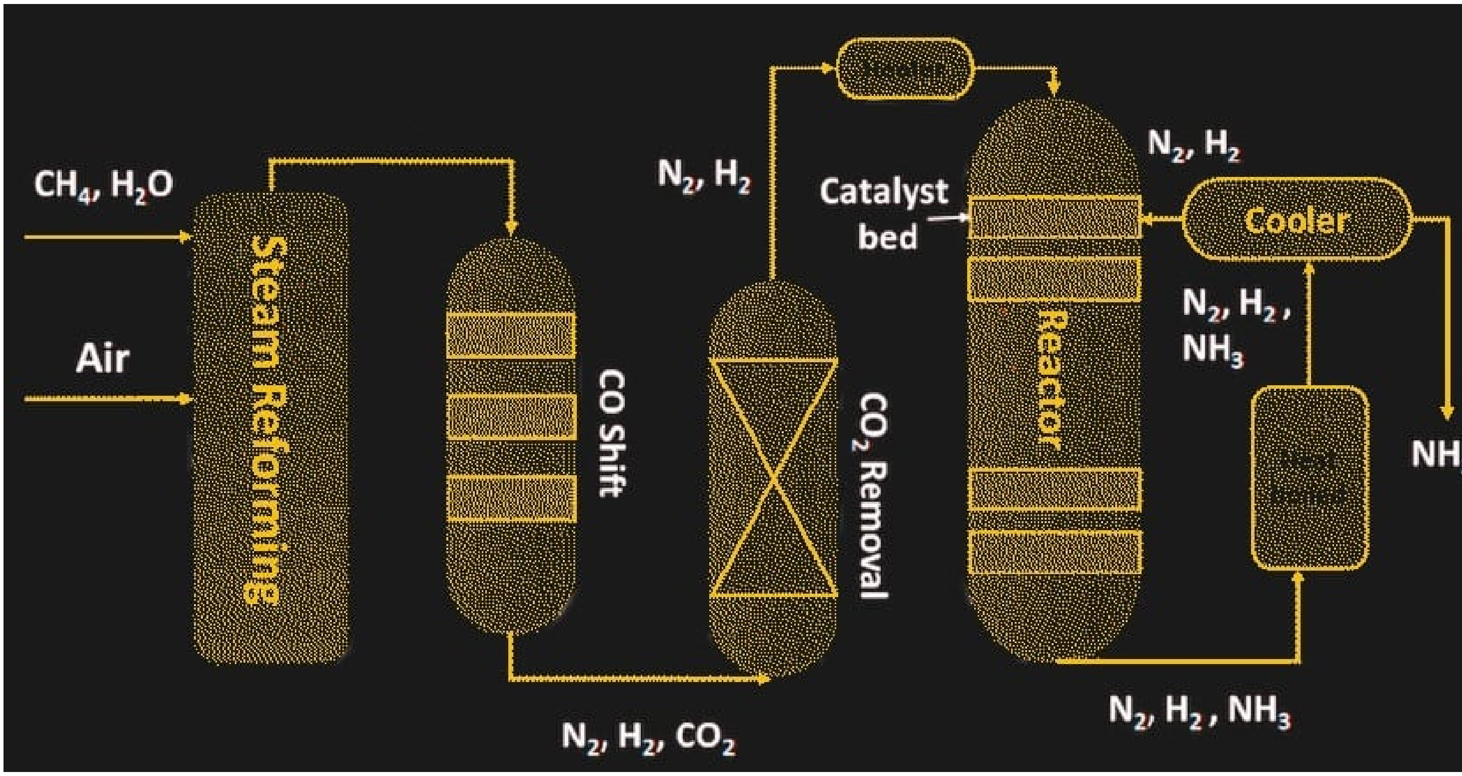
Pam Silver and Dan Davidi (The SynBio Hive at Harvard Medical School) are exploring ways to enhance both synthetic and artificial photosynthesis. One approach involves generating myriad different forms of key photosynthetic enzymes (e.g., RuBisCO, the most abundant protein on the planet) and then leveraging their expertise in single-cell assay development and genome engineering to improve photosynthesis in photoautotrophic microbes as well as plant cultures in suspension. This system allows them to take advantage of the power and scale of single-cell high throughput screens while maintaining relevance to plant physiology. This has the potential to greatly decrease the time, scale, and cost needed to develop desired plant phenotypes.

In an alternative approach to enhancing natural photosynthesis, they propose to optimize an artificial photosynthetic system that couples the electrochemical production of hydrogen gas to power microbial growth. This offers two major advantages (1) ~10 times greater efficiency in converting solar energy to biomass than photosynthesis in plants, and (2) greater metabolic plasticity, as microbes are much more amenable to genetic engineering, editing, and synthetic biology manipulations compared to plants. They propose to use *Xanthobacter autotrophicus* – a bacterial strain that performs carbon and nitrogen fixation and uses hydrogen as an energy source – for sustainable and efficient bioproduction. They will maximize the performance of their bionic photosynthetic system by developing genetic engineering tools to apply directed evolution, and rationally designing nitrogenases, rubiscos, and hydrogenases – the key enzymes required for N2,

CO_2, and H2 uptake. This will produce valuable metabolite commodities starting from only air, water, and renewable electricity.

For the screening platform: Croplands worldwide occupy 18.6 million km2 and assimilate about 10 Gt/y. of CO_2 eq. Modeling suggests enhancing photosynthesis can lead to up to a twofold increase in crop yields. Thus, assuming the screen can lead to a conservative 10 percent increase in crop yields by selecting for cells with enhanced photosynthesis, and if 10 percent of the crops globally could be replaced with enhanced crops developed via the screen, their approach has the potential to sequester 10 percent*10 percent10Gt/y = 0.1Gt/y.

For the electrochemical production: The bionic leaf system for converting photovoltaic energy to biomass is ~10 times more efficient than that of natural photosynthesis. Thus, for every unit of solar energy invested, they will fix 10-times more carbon compared to crop land. Assuming the equivalent of 0.1 percent of croplands will be used for electrochemical production (note that this system can be placed in lands that are not suited for agriculture), they would sequester 10Gt/y*0.01*10 = 1.0Gt/y as microbial biomass. They note that this number is a lower bound estimate because the microbial system does not rely on Haber-Bosch derived nitrogen and thus has a lower carbon footprint compared to crops.



The Haber-Bosch process has been incredibly useful since its invention, but now greener technologies may supplant it. Credit: Palma et al,

Ken Nealson (Project Vesta; Professor Emeritus, University of Southern California) described a project involving microbial acceleration of the natural process of silicate-carbonate mineral weathering as a method of atmospheric CO_2 drawdown. There is general agreement that rock weathering via the conversion of basaltic (silicate) rocks to limestone-like carbonates offers an excellent (and irreversible) way to reduce atmospheric CO_2 levels. The natural rates of such weathering reactions are very slow, but Project Vesta is developing living microbial catalysts that greatly enhance the rate of this weathering. Preliminary work has shown major rate enhancement(s), and the project is now ready to begin screening and genetically engineering microbes to maximize the rate(s) at which they accelerate silicate weathering. The next step will be to scale up to 3,000-liter reactors, followed by medium and then large-scale reactors. Vesta anticipates about 5 million tons of carbon removal per year with current supply partners, and after that there are sufficient mineral reserves and mine tailings to scale beyond the gigaton level in less than a decade. Their approach will encompass coastal, terrestrial (soil) and freshwater mineral enhancement, and include both reactor-based and in-situ systems. Project Vesta has the capability to bring the described approach(es) to scale rapidly, using several labs and field stations where research is ongoing, together with an outstanding scientific, engineering, and administrative staff, already working on permitting and other business issues.

Tobias Erb (Max Planck Society) leads a large team looking for ways to improve photosynthesis beyond its natural limits. Plants generally use only about 1 percent of the sunlight that falls on them to make carbohydrates, consuming or “fixing” atmospheric carbon in the process. Excellent research teams around the world are exploring ways to improve natural photosynthesis and have made considerable progress to date. But Erb and his colleagues are taking these efforts a step further and are on track radically to reinvent photosynthesis using synthetic biology, enzyme engineering and machine learning to create innovative crops featuring a new-to-nature CO_2-fixation metabolism with photosynthetic yields increased by 20 percent to 60 percent (potentially up to 200 percent). They have already demonstrated several synthetic pathways for improved CO_2 fixation that are up to 20x faster than natural photosynthesis and require 20 percent less energy in the lab. Erb’s team is working to implement these new-to-nature solutions in microorganisms and plants to improve their CO_2 uptake efficiency beyond the limits set by natural evolution. Models suggest that their approach could lead to the ability to sequester upwards of 3 GT of CO_2 equivalent annually, if applied to crops alone.

Forest Biotech company FuturaGene (parent company Suzano SA, Brasil) is focused on the sustainable enhancement of renewable plantation forest species. Plantation forests constitute only 7 percent of global forest area, but they provide ~50 percent of industrial wood. Shortfalls of 1-4 billion m^3 in industrial roundwood supply are projected by 2050, and the productivity of planted forests must triple by 2050 if global climate mitigation and adaptation targets are to be supported and destruction of natural forests prevented. FuturaGene proposes within the next 10 years to deploy genetic modification (GM) technologies (including direct yield-enhancement and photorespiratory bypass) to plantation forestry across the sub-tropics to address those targets and has the ability through parent company Suzano SA to do so at scale. FuturaGene has developed and deregulated (in Brazil) a direct yield-enhanced eucalyptus variety, which is ready for landscape level testing. Current carbon sequestration is estimated to be around 240 tonnes per hectare during a seven-year growth cycle (a 2015 desk study). A 12 percent increase in yield by either route would deliver 270 tonnes/ha/7 years. If yield enhanced clones were planted over the entire 1.2 million ha estate of Suzano this would correspond to 324 million tonnes CO_2eq per cycle. Across the entire Brazilian estate of 9 million hectares this would be 2.4 GT CO_2eq per cycle.

Xiaohan Yang (Oak Ridge National Lab) proposed, in some detail, a well-documented and justified 3 pronged mutually reinforcing approach to carbon sequestration and climate change adaptation. This would involve increased photosynthesis, increased translocation of captured carbon, and increased soil capacity—and would, if successful, have a major impact. (This proposal was not presented in the workshop, but instead developed pursuant to conversations at the workshop and added afterwards.)

The 3 objectives are (i) integrative engineering of CO_2 capture, storage and utilization in fast growing poplar (which can be used as a feedstock for biofuels, biomaterials, and engineered for deeper roots and root architectures for increased carbon storage); (ii) genetically enhanced agave-mediated carbon sequestration and utilization in dry and hot regions; and (iii) the development of “care-free/climate-friendly” lawn grasses. It is noteworthy that increased production of agave would not only contribute to amelioration of malnutrition which will become increasingly serious as the climate changes, but it would enable utilization of the planet’s 500 million acres of marginal land (arid and semi-arid) for production of agave and poplar, and for the sequestration of 18 Gt CO_2eq per year of atmospheric carbon. In addition, the crassulacean acid metabolism photosynthesis pathway, which would be utilized, has the unique feature of high water-use efficiency due to daytime closure of stomata for reducing water loss mediated by transpiration, and night-time opening of stomata for CO_2 uptake. More generally, CAM genes could also be engineered into C3 plant species to increase drought tolerance.

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All of these gene editing strategies could be integrated with other interesting ideas on carbon capture and sequestration. Credit: Rita Erven via GEOMAR

Applying “care-free/climate-friendly” varieties of perennial ryegrass, tall fescue, Kentucky bluegrass and fine fescue that are used in lawns, athletic fields, golf courses etc. will lead to significant reductions in mowing frequency, fertilizer inputs, and water use, and could result in a greater than 90 percent reduction in emission of CO_2, nitrous oxide and methane associated with lawn care. Several studies have shown that greenhouse gas emission from lawn care, which includes fertilizer and pesticide production, watering, mowing, and other lawn care practices, is much greater than the amount of carbon stored by lawngrasses. Yang estimates that in the US alone lawn care practices contribute at least of 41.3 million metric tons of CO_2 eq.

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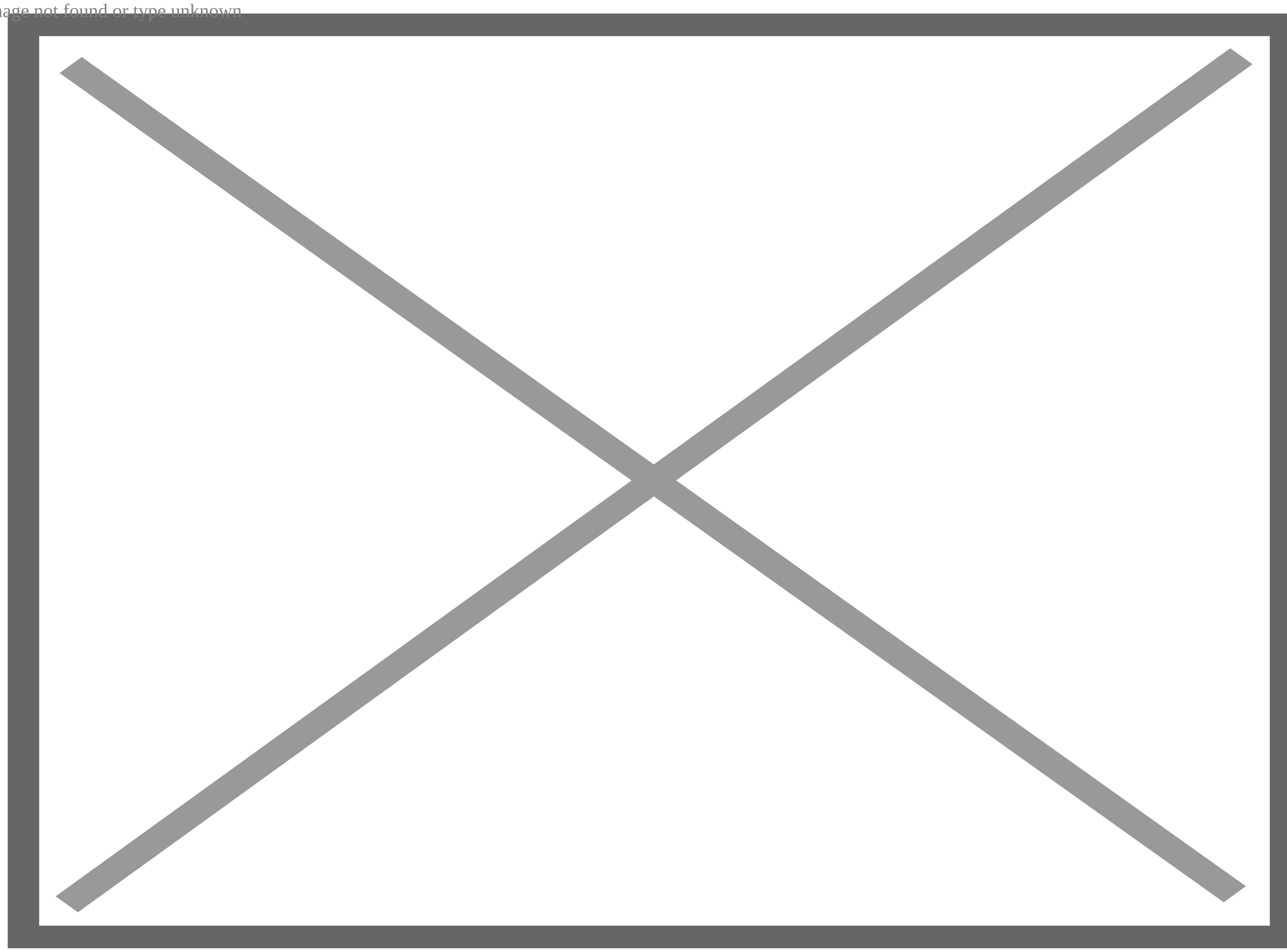

This picture seems to suggest that the U.S. uses about 1000 gallons of water per day, per person.

Val Giddings (Information Technology and Innovation Foundation) pointed out that while applications such as those explored in the workshop hold considerable GHG mitigation potential, the rate limiting factor in their ability to sequester carbon is implementation, which is contingent on public acceptance. Policies, regulations, and business practices such as industry certification all create considerable barriers to development and deployment of innovative solutions developed with gene editing and genetic engineering. This is the case around the world despite the lack of scientific justification for such discrimination, and in the face of massive experience demonstrating superior safety and sustainability of such technologies. If the acceptance climate is not improved these solutions will not be deployed. Pushing back against the concerted disinformation campaigns from special interests that have driven such discriminatory policies is difficult, particularly for governments, but independent, science-based voices are uniquely suited for the task. There are several entities with proven track records in this space, a handful of which are listed below.

- The Genetic Literacy Project (GLP)
- The Institute for Food Agricultural Literacy (IFAL)
- The International Service for the Acquisition of Agri Biotech Applications (ISAAA)
- PG Economics
- The Information Technology and Innovation Foundation (ITIF)

Each of these entities is vulnerable to extinction due to financial uncertainty.

Workshop participants are united in the view that these groups are deserving of support as critically important contributors for enabling future innovations built on genetic technologies. In addition to general support for the ongoing activities of each of these groups, there is a particular need for outreach in the service of alliance building between researchers and receptive environmental NGOs and communities of faith. The most promising opening in decades to receptive environmental NGOs is being pursued by FuturaGene and needs external support. At least one of FuturaGene's projects is ready for immediate implementation and could provide validation of the approaches of this suite of initiatives fomenting a vital public acceptance breakthrough. Meanwhile the GLP is poised to reach out to communities of faith, building on previous efforts in this space, and also in need of external support.

In summary, many opportunities exist for synergies and cooperation between the several projects described. It follows that the benefit of supporting the projects as a group would be greater than picking and choosing projects to support as from a menu of discrete offerings, and sustained support over time with minimal bureaucratic burden would lead to the greatest returns on investment.

There is agreement across several proposals that the optimal way to reduce CO2 is to improve biological productivity through crop engineering and increasing carbon fixation rates. There is also recognition that nitrogen use efficiency, as mediated by the soil microbiome, is essential to achieving this goal. To further decrease GHGs outside of crop systems, microbial processes including atmospheric methane oxidation and siderophore-mediated silicate weathering have been proposed. Organization to leverage the outputs of the projects described could center around the plant-microbe-geo axis with feedbacks between the atmosphere and hydrosphere. The idea would be to integrate implementation and monitoring of the proposed technologies to incorporate and include synergistic (and unintentional) effects across other eco-spheres (e.g., biosphere, atmosphere, geosphere, hydrosphere). An organizational strategy that interconnects across systems would allow additional projects to be incorporated so long as the intention is to remain conscious of the interconnections and feedbacks. This strategy will also force us to keep in mind that systems necessarily work together and affect one another. We cannot afford to continue the age-old practice of changing one component of a system with the belief that nothing else will change in response!

Adding the estimates from each of the applications described above, the total carbon sequestration capability of projects described in this report is estimated to begin at ~18 Gt CO2eq.

In conclusion, it is appropriate to remember the most important policy issue of all: when considering technologies for climate change mitigation, the all-too-well-known risks of doing nothing must be weighed against the unknown (but almost certainly much smaller) risks of doing something. The failure to develop a perfect solution must not be allowed to prevent measures that offer considerable improvement over inaction. In medicine, high-risk experimental therapies are regularly and rightly justified when the alternative is terminal. It must be borne in mind that we are all together on a road towards considerable planetary warming with massively severe consequences if we do nothing.

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