The potential of molecular biology and biotechnology for dealing with global warming

The biosciences will have to play a leading role in developing new technologies for mitigating the impact of greenhouse gas emissions

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The Paris climate conference last December was heralded as the first major breakthrough to set concrete targets for dealing with global climate change. The signatories, including the major industrial nations, finally agreed to limit their greenhouse gas emissions in order to limit the global temperature increase to 2°C from pre-industrial levels by 2100. In addition, Article 5 of the Paris agreement requires that “Parties should take action to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases” (<http://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf>). While it does not explicitly mention it, the agreement thereby throws down a gauntlet to scientists and biotechnology to accelerate their efforts on creating technologies that would help the world to keep atmospheric CO₂ levels in check while preserving the environment.

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Indeed, agriculture and forestry are fertile grounds for applying biotechnology: They are not just major contributors to climate

warming but also play a potential role in reducing emissions. Agriculture generates more than a quarter of global greenhouse gas emissions, while the combined impact of forest fires and deforestation accounts for another 20% (<http://www.un-redd.org/aboutredd>). Vice versa, forests are major carbon sinks and have a lot of potential to sequester CO₂ from the atmosphere. Agriculture will have to play a crucial role for sustainable energy production.

The task for molecular biology would fall into two categories while overlapping with a third. The first is the development of new technologies for solar energy conversion, not just for generating electricity, but also for synthesizing carbohydrates from atmospheric CO₂ for fuel and as raw material for the chemical industry. The second category focuses on plant biotechnology to increase food production and carbon sequestration. In addition, there is an ecological dimension to mitigate greenhouse gas production and preserve the environment and biodiversity.

Photovoltaic (PV) panels already make a major contribution to the 21% of global electricity production from renewable sources along with wind, biomass, and hydropower (http://www.eia.gov/forecasts/archive/ieo13/more_highlights.cfm). But PV only produces electricity, which is why sustainable sources only account for 11% of the total energy consumption, as their contribution to solid fuels is negligible. Harnessing the power of

photosynthesis could therefore yield electricity along with a variety of fuels such as hydrogen, butanol, and more complex hydrocarbons. A further benefit of studying photosynthesis is that it can help to improve the light-harvesting efficiency of current PV panels.

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There are two major strategies for solar energy conversion: engineered organisms, such as algae, and artificial systems that mimic the ability of the chloroplast or cyanobacteria in converting light, carbon dioxide, and water into hydrocarbons. Not surprisingly, the first branch is more mature since it is easier to tinker with natural systems, which have evolved over millions of years to reduce CO₂ effectively, than to start from scratch. But completely artificial systems may eventually have greater potential, according to Peidong Yang, Chair in Energy at the Department of Chemistry, University of California, Berkeley, in the USA, although he concedes that there are still fundamental problems to solve in developing the catalysts that drive CO₂ reduction.

The photosynthetic process involves harvesting sunlight and fixing CO₂ to yield oxygen and simple carbohydrates. The two most fundamental components are the light-harvesting antennae and the catalysts that reduce CO₂ and oxidize water. The light-harvesting part is much easier to fabricate artificially, and already “the efficiency of solar panels is high, much better than Nature can do”, according to Yang. Plants and bacteria have to make do with proteins, which fulfill many tasks but are not optimal for light harvesting.

Yet, it turned out that the CO₂ reduction chemistry in the chloroplast was even harder to reverse-engineer than had been expected. “Right now, in the synthetic version, we can do CO₂ to CO but anything beyond CO is very difficult”, Yang said. “So about 6 years ago my group started to look back into Nature and see how to utilize bacteria for the chemistry itself”. This eventually yielded a hybrid system that combines an artificial semiconductor for harvesting light with a bacterial cell to perform the catalytic reduction [1]. “Light goes into the semiconductor nanostructure, producing an electron passed onto the bacteria, which then takes in CO₂ and produces products like acetate, methane and later on, after an upgrade, butanol”, Yang explained. As the nano-structured semiconductors have greater light-capturing potential, Yang is optimistic that such hybrid systems have the potential to generate fuels on a commercial scale. “Now we are using much simpler semi-conductors to do the photo sensitization, which is necessary to scale up for the future”.

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Yang is also convinced that purely synthetic systems will eventually win out, because they can be more robust than biological components. His and other teams are therefore probing more deeply into the catalytic mechanisms for CO₂ reduction that have evolved in bacteria. “When we looked in more detail at the molecular level we found that there are multiple enzymes

working collectively to finally give you one product”, Yang explained. “This is telling us that in order to do synthetic catalysis, maybe we need multiple catalysts in what I call tandem catalysis. [...] So that is a big message that by exploring this bio hybrid approach we can learn from bacteria to design a better synthetic version”.

Thomas Meyer, Director of the University of North Carolina’s Energy Frontier Research Center in Solar Fuels and Next Generation Photovoltaics, and his group have taken a different approach and adopted the dye-sensitized photoelectro-synthesis cell, or DSPEC. These cells combine a light-absorbing molecule with catalysts for water oxidation and CO₂ reduction on a semiconductor surface chosen for their potential to operate at higher temperatures and voltages. One advantage is that light harvesting, electron transmission, and the catalytic reduction take place within an integrated system in which each component can be synthesized, evaluated, and improved independently of the others. This includes a photoanode for water oxidation, which yields oxygen and hydrogen, and a photocathode to reduce CO₂ to CO and oxygen.

Yet, Meyer commented that going beyond CO remains a major challenge. “The problem with CO₂ is reduction past the 2e- stage through HCOH to methanol and hydrocarbons”, he said. “This is still largely uncharted territory for molecular catalysts but Cu metal electrodes and Cu nanoparticles can do it and there has been some recent progress on nanoparticle alloys”. Nonetheless, Meyer believes that the DSPEC approach will eventually go all the way to synthesizing hydrocarbons by recycling atmospheric CO₂. He also agreed that in the end, wholly artificial systems would prevail. “Given the demands for turnover and lifetime and the motto ‘keep it simple stupid’, artificial systems will probably win the day”, he said.

While solar energy conversion promises to bear down on greenhouse gas emissions in the long term, there will be a period of a century or more of elevated global temperature and CO₂ levels. The second big research challenge thus lies in assessing the ecological impact on plants in particular, along with mediating the consequences. More CO₂ and higher temperatures would be expected to

stimulate plant growth and help sequester some CO₂ by increasing the global volume of living plant material. But there are many confounding factors, notably the availability of water, nitrogen, and phosphorus.

Plants indeed make more efficient use of water at higher CO₂ levels, which could help to offset greater evaporative loss through rising temperatures. This might lead to an increase of biomass of up to 33%, but that effect goes away when nitrogen or water become limited [2]. Similarly, phosphorus could significantly constrain the CO₂ fertilization effect, according to Peter Reich, head of forest ecology at the University of Minnesota. He therefore stressed the importance of taking nutrient constraints into account when calculating future atmospheric CO₂ levels. “The main implications involve the role of the terrestrial biome in slowing down climate change. If widespread nutrient limitations constrain the capacity of forests and grasslands to absorb part of the extra CO₂ we put into the atmosphere from fossil fuel emissions, then the concentration of CO₂ in the atmosphere will rise faster than it might otherwise and that most models predict, with climate changing faster too”, Reich explained.

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The positive impact of temperature on plant growth will also be constrained by water. “In ecosystems that are cold-limited, warming may enhance production, although it could increase productivity but not sequestration if decomposition was stimulated by a similar or greater extent”, Reich said, adding the warming could even further reduce plant growth in areas with water deficits.

Another major factor is the different response between the two major categories of plant distinguished by their mode of photosynthesis: C3 and C4 plants. C3 plants fix carbon through the Calvin cycle, where the first product is a 3-carbon compound. The enzyme Rubisco regulates the uptake of CO₂ and rate of photosynthesis in a single-staged process, which is well adapted for plants in cool, moist conditions under normal light levels.

C4 plants evolved more recently and are better adapted to arid conditions where light is plentiful but moisture is scarce. They still use Rubisco to control photosynthesis, but first synthesize a 4-carbon compound, using an additional enzyme called PEP carboxylase that fixates CO₂ very quickly during strong sunlight, thereby reducing the time the stomata need to be kept open, and so keeping water loss to a minimum. However, this additional step consumes additional energy, and C4 plants are therefore less well adapted to cooler, wetter conditions. C4 plants include about 3,000 known species in 19 families, such as saltbush, corn, many annual plants that flower in summer, and grasses in arid and tropical regions. The much larger C3 category includes barley, sunflower, rice, tomatoes, wheat, peanuts, sugar beet, oats, and most trees, as well as many weeds, and cool-climate grasses.

Finally, CAM evolved as an even more specialized adaption for extreme arid conditions in succulents such as cacti, agaves, and some orchids. The stomata open to admit CO₂ only at night to further minimize transpiration water loss. As photosynthesis can only take place during the day under sunlight, CAM plants first convert CO₂ into an acid for storage. The reaction is then reversed the following day to bring back the CO₂ for photosynthesis.

C3 plants are expected to gain more from elevated CO₂ because it would enable them to survive in more arid areas. However, it is not quite as simple, given that temperature also has to be taken into account. “C4 plants are largely insensitive to CO₂ levels because they possess a compression mechanism”, explained Linus Gog at the Department of Plant Biology, University of Illinois at Urbana-Champaign. “However, they are very sensitive to temperature, so they are indirectly responsive to rising CO₂ levels. All in all, predicting how the landscape of plants will change over time is still a matter of speculation because it depends on so many different environmental factors”.

One such factor is the relationship with predators, including alterations of the plant's immune system and nutrient value. A study by Jorge Zavala and colleagues at the Institute for Genomic Biology at the University of Illinois suggested that elevated CO₂ typically increases the concentration of leaf carbohydrates and, in

combination with higher temperature, decreases nitrogen content [3]. This means that some herbivores, including many insects, are likely to consume more foliage to meet their nutritional needs.

Zavala is also involved in ongoing research indicating that higher CO₂ might weaken plant defenses. “Currently we are studying the mechanisms that induce the down-regulation of hormones associated with plant defenses against insects under elevated CO₂”, he said. “We think that high photosynthesis levels might be responsible for down-regulation of plant defenses, by inducing salicylic acid that inhibits jasmonic acid”. However, it might also be that rising temperature stimulates plant defenses. “We think that heat shock proteins are responsible for the up regulation of defenses, increasing ethylene emission and allowing an increment of both salicylic acid and jasmonic acid”, Zavala explained.

These and other studies provide the knowledge base for adapting plants to changing climate conditions, or to reduce their contribution to greenhouse gas production. This is the case in particular for rice, which produces methane, a potent greenhouse gas, through its associated soil microbes, especially in flooded fields [4]. An international team from Sweden, China, and the USA reported that methane production could virtually be eliminated by splicing a single barley gene called SUSIBA2 into the rice genome. It alters the photosynthetic mechanisms to direct carbon toward the grain and leaves instead of the roots, thereby increasing starch levels and yield as a byproduct [5]. “SUSIBA2 is a transcription factor which positively regulates or upregulates genes for biomass synthesis in above-ground tissues where SUSIBA2 is expressed, such as seeds and stems”, explained the study's lead author Chuanxin Sun from the Swedish University of Agricultural Sciences. “Increased biomass synthesis in above-ground tissues results in less carbon allocation to root exudates for consumption of methane-producing microbes, and in consequence less methane is produced”.

Another major research focus is adapting crop plants to various aspects of climate change, especially drought. The first commercialized drought-tolerant maize (MON87460), expressing the *Bacillus subtilis* cold-shock protein B (cspB), has already been planted by 2,000 farmers over 50,000

hectares in the USA [6]. Meanwhile, Indonesia has approved drought-tolerant sugarcane expressing choline dehydrogenase (betA), which accumulates glycine betaine in response to drought to adjust osmotic flows across cell membranes [6].

Rice is again the crop of choice for India's M.S. Swaminathan Research Foundation that collaborates with the University of Tasmania, Australia, to develop salt-tolerant varieties that can grow in low-lying areas where saltwater mixes with groundwater. The project exploits the wild rice variety (*Oryza coarctata*) that is capable of growing in saline conditions, to identify genes involved in salt tolerance and engineer them into rice cultivars (<http://www.mssrf.org/?q=content/mssrf-receive-funding-develop-salt-tolerant-rice>).

Yet, a lot of such work is controversial given the continued resistance to genetically modified plants. Sun pointed out that his low-methane GM rice was banned in China, which meant that alternative approaches such as genome editing would be needed to develop alternatives. But the growing urgency of dealing with climate change has led to renewed ambition by the biotech industry and many academic researchers to combat green theology and finally convince the public that GM has a crucial role to play for the decades to come.

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