Workshop on
The Role of Biotechnology in Mitigating Greenhouse Gas Concentrations

June 23, 2001

A Workshop Summary

by

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Workshop Cochairs

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Executive Summary

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Office of Biological and Environmental Research

On June 23, 2001, the U.S. Department of Energy (DOE) held a workshop of biotechnology leaders to examine potential roles for biotechnology on mitigation of greenhouse gases and their effects on climate. The workshop participants discussed a wide range of possible biotechnology solutions to reduce atmospheric concentrations of greenhouse gases, the use of biomass for fuel production, and the use of biological processes to make cleaner fuels with higher energy content. This Executive Summary was prepared by DOE staff in response to the workshop summary, prepared by workshop cochairs Drs. Venter and Nealson, to link the range of biotechnology solutions discussed to DOE mission needs.

Solutions for Carbon Sequestration Using Microbes and Plants

- Plants can be modified so that they take up more carbon from the atmosphere and retain more of this carbon in an inaccessible form when they die and decompose.
- The mix of microbes found in complex microbial communities in soil can be altered to enhance the long-term retention of soil carbon. Generally, more carbon in soil also has broad positive benefits for soil fertility and water retention.
- The ability of the ocean's microbial communities to remove carbon from the atmosphere and deposit it permanently in the deep ocean can be enhanced. But first, this possible solution must be proved environmentally acceptable. Advanced biotechnology techniques can help make this determination.

Use of Biomass for Fuel Production

- Plants can be modified to
  - grow places they wouldn't normally grow
  - grow faster and more efficiently
  - be more easily harvested
  - contain material more easily converted to clean energy
- Microbes can be used as sources of biomass for energy because they can be readily modified and will grow in industrial environments and/or inhospitable natural environments.

Use of Biological Processes to Make Cleaner Fuels with Higher Energy Content

- Microbes carry out some chemical processes better than comparable solutions designed by people. Thus, microbes or their products can be used to convert sunlight, hydrocarbons, or biomass to useful energy products without the production of greenhouse gases such as CO_2. These types of biological conversions can operate under a wider range of conditions than traditional industrial approaches.

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Climate change is one of the most challenging global issues of the 21st century. It will touch everyone and needs to be addressed on a time scale unlike anything humankind has ever undertaken. The potential impacts of action (or inaction) will affect economies rich and poor, human health, and the global environment. President George Bush has called for *" . . . an effective and science-based response to the issue of global warming,"* with an emphasis on technology, including biotechnology solutions.

On June 23, 2001, the U.S. Department of Energy (DOE) convened a workshop of biotechnology leaders to examine the influence that 21st-Century Biology could have on mitigation of greenhouse gases and climate effects. Dr. J. Craig Venter, President of Celera Genomics Corporation, and Dr. Ken Nealson of the Jet Propulsion Laboratory at the California Institute of Technology led the workshop. Dr. Ari Patrinos, Associate Director for Biological and Environmental Research of the Office of Science at DOE challenged the participants to look for opportunities that would bring together the many science and technology disciplines needed to make the necessary scientific advances for developing innovative solutions to the climate-change problem. The workshop examined the underlying economics and carbon intensity of the world's energy system, focusing on the potential for biofeedstocks, bioconversion, and carbon sequestration to meet the challenge. The workshop concluded with a sense of optimism that biotechnology is indeed poised to address this global challenge by developing (as Ari Patrinos charged the group) "*innovative solutions along unconventional paths*."

This report captures the essence of the workshop discussion. Key scientific and technical challenges associated with climate change and increasing concentrations of greenhouse gases were identified and discussed. Much of the focus was on those challenges for which realistic (though challenging) biotechnology solutions exist.

A Global Framework – The Challenge of Greenhouse Gases: The climate problem is indeed daunting. Greenhouse gas concentrations are higher today than at any time in more than 420,000 years and may become the highest in 23 million years.

According to Jae Edmonds, "*The cumulative nature of the problem implies that each generation lives with inherited greenhouse gases and with only marginal control over its current climate*."

There are many greenhouse gases, the most important of which is carbon dioxide (CO_2) because of its abundance and long lifetime in the atmosphere. About 7.5 billion tons, or 7.5 gigatons, of carbon are released into the air by human activity each year, 80% from the burning of fossil fuels and the rest from deforestation and other changes in land-use. Although this number is small (less than 5% of the total) compared with the amount of carbon that nature regularly transfers among the air, land, and oceans, there is solid evidence that the increase in atmospheric CO_2 concentrations documented since pre-industrial times is due to human activity.

Controlling the concentrations of most air pollutants means that their emissions are stabilized at some maximum level, and this also is true for most greenhouse gases. But CO_2 is different because it cycles through the biosphere and is never actually removed as the CO_2 levels in the atmosphere and oceans slowly equilibrate over centuries. Therefore, the only way to actually stabilize CO_2 at *any* level is to reduce the net global emissions of CO_2 to zero. This must happen regardless of any final CO_2 concentration that society determines is necessary to "prevent dangerous anthropogenic interference with the climate system."

Technology Solutions for Controlling Carbon: *"Biotechnology can change the nature of the problem . . . if it can change the economics of a major part of the global energy system, for example, commercial biomass; carbon capture; and hydrogen, fuel cells, and transportation technologies."* (Jae Edmonds)

The scale of the global carbon challenge is immense, measured in ***billions*** of tons of carbon ***every year***. This amount of carbon (if it were a liquid) is equal in volume to about three days' flow of the Mississippi River. The cost of reducing these cumulative global CO_2 emissions must be controlled and reduced because the global need for energy will continue to increase as people everywhere seek economic progress. Thus, the future balance between increasing energy demands and concerns for climate change due to greenhouse gases will depend on new strategies that couple science and technology solutions, energy services, and CO_2 emission reductions.

Jae Edmonds suggested that "*a number of technical solutions could together address the challenge if their costs can be made attractive."*

1. Initiating commercial biomass energy production—growing plants primarily for their energy content, as opposed to their food or material properties.
2. Capturing carbon from fossil fuels—so that the CO_2 never enters the atmosphere after combustion, or even before combustion, by turning fossil fuels into sources of hydrogen, which combusts to water.
3. Capturing and sequestering carbon in the Earth's subsurface, terrestrial, or ocean reservoirs—using either such natural processes as soils, forests, or oceans, or such geologic formations as depleted oil and gas wells, coal seams, or deep brine reservoirs.
4. Producing hydrogen using biological processes.

There will be no single solution to the climate change problem. Instead, many solutions together will be needed to provide energy and remove carbon at scales significantly greater than those required to meet our current energy system requirements. The biological sciences can and must play a central role in providing solutions in the 21st century.

Biotechnology Solutions and the 21st Century Biology Revolution – Focus on Microbes: The availability of complete genome sequences for all manner of life on Earth has opened a new era and new opportunities in biology. Craig Venter assured the group that *"the genome sequencing enterprise is up to the challenge."* Further, Toby Bradshaw added, "*We need a better fundamental understanding of the organisms that contain the vast majority of terrestrial biomass."*

For all intents and purposes, ours is a world filled with microscopic creatures that we take for granted and almost never know even exist. Microorganisms are earth's recyclers, participating in the recycling of most biological materials on earth. In the process, they produce and, together with plants, take up greenhouse gases.

During some 4 billion years of their evolution, microbes long ago solved many problems for which we are seeking solutions. Estimates are that more than 99% of Earth's genetic and metabolic diversity *and, importantly, its source of biological solutions to diverse problems* reside in the microbial universe of bacteria, fungi, archaea, and minute protozoa and micro algae that collectively compose the planktonic communities in the oceans and the majority of life in soil. Indeed, he Earth's biomass is estimated to be 60% microbial. Because so many chemical reactions take place on surfaces and because in comparing the differences in size of the cells of individual microbes with the cells of other organisms, microbes are even more important because they have about 95% of the biologically active surface area on the planet. If we want to solve problems using biological approaches rather than relying only on technology-based solutions, the microbial world is the place to explore.

Clearly, fundamental knowledge about the makeup, functioning, and capabilities of microbes and microbial communities is needed if we are to understand the consequences of climate change on ecosystems and to make the best use of opportunities offered by these communities to develop biotechnology solutions for addressing the challenges of global change.

DOE already has begun to take advantage of the untapped potential of microbes through a number of research programs including the Genomes to Life program, a new research effort that will contribute basic knowledge, innovative technology, and computational infrastructure to help usher in this exciting new era. Because of their relative simplicity and dominance on Earth, microbes will be the focus of the program. However, the knowledge gained and the technologies developed will apply to our understanding of biology across all species. Genomes to Life will identify the molecular machines of life—the multiprotein complexes that carry out the functions of living systems. The program also will characterize the gene regulatory networks and processes that control these molecular machines. Finally, Genomes to Life will characterize the functional capabilities of complex microbial communities in their natural environments.

The comprehensive systems approach to biology spawned by the genome projects will be applied to provide a deeper understanding of biological function through the development of a new generation of technologies that bypass the traditional single-gene, single-protein approach and allow scientists to study the full complexity of living organisms, even their systems.

The first phase of Genomes to Life already is under way in the Microbial Cell Project. This Project is defining the global interactions among proteins and other biomolecules and also will identify specific functional networks in microbes and, eventually, in higher organisms. Computational methods, an essential component of tomorrow's biology, are being developed to simulate these functional pathways and regulatory networks in microbes. These techniques will revolutionize the study of microbes from terrestrial to ocean ecosystems that control global carbon cycling and its ultimate sequestration as well as the potential use of microbes in the generation of clean energy.

Basic research supported in Genomes to Life will quickly translate into practical applications. Research on the enzymes, regulation, and environment of the carbon cycle will lead to new biological strategies for storing and monitoring carbon. Understanding metabolic pathways and their regulatory networks will allow us to more effectively use or modify microbes or plants that produce and convert biomass for fuel, power, and products; sequester more carbon; or help clean up environmental contaminants. Harnessing metabolic or regulatory pathways in H_2-producing microbes could, for example, provide an alternative and clean energy source.

As expected, a substantial portion of the discussion at the workshop focused on microbes. In addition to the benefits and advantages of using microbes to help address a number of DOE mission needs, as noted above, some more fundamental reasons why microbes offer such great promise include the following:

- Microbes are readily manipulated, providing opportunities for use and modification.
- Microbes have short generation times compared with those of plants—shortening the times needed, for example, to modify genetic structure and function or to produce large amounts of specific organisms or biological products.
- Microbial processes often are scaleable from laboratory to industrial settings.

Solutions for Carbon Sequestration Using Microbes and Plants

- Plants can be modified so that they take up more carbon from the atmosphere and retain more of this carbon in an inaccessible form when they die and decompose.
- The mix of microbes in complex microbial communities in soil can be altered to enhance the long-term retention of soil carbon. Generally, more carbon in soil also has broad positive benefits for soil fertility and water retention.
- The ability of the ocean's microbial communities to remove carbon from the atmosphere and deposit it permanently in the deep ocean can be enhanced. But first this possible solution must be proved environmentally acceptable. Advanced biotechnology techniques can help make this determination.

Terrestrial Carbon Sequestration: "*An environmental or ecosystem genomics approach allows for discovery of unique combinations of traits important for biomass and carbon sequestration, which are not often found when looking at individual plants and microbes*." (Stan Wullschleger)

The annual and ongoing capture and sequestration of multigigaton amounts of CO_2 on a global scale are central to the success of future strategies to mitigate atmospheric greenhouse gas concentrations. Storage of CO_2 in ocean and terrestrial ecosystems and in geologic formations is the only option for sequestering the hundreds of gigatons of carbon that will have to be dealt with in the coming decades. Large-scale sequestration in the natural environment, sometimes referred to as "Enhancing the Natural Carbon Cycle," requires a much more complete understanding of the global carbon cycle.

Jae Edmonds reminded participants "*Biological systems are the principal way to sequester CO_2 that is already in the atmosphere*." Photosynthesis in terrestrial ecosystems, with subsequent storage as biomass and in the soil, already removes 2 gigatons of captured carbon annually from the air; a total of about 60 gigatons of carbon cycles between the atmosphere and terrestrial ecosystems. Soil, which has two-thirds of all terrestrial organic carbon, is of particular importance over decades and centuries, and inorganic soil carbon is an even larger pool. Strategies for enhancing terrestrial carbon sequestration include increasing the above- and below-ground components in managed or unmanaged ecosystems, as well as learning how to avoid loss of carbon to the atmosphere, such as from northern temperate peat lands with global warming. The question is, "*Is it possible to increase and sustain the annual removal of atmospheric carbon from the present value of 2 gigatons to 3, 4, or even more gigatons?*"

Managed ecosystems include forests, farms, and rangelands. Because we know how to manage these systems, they are realistic targets for enhancing carbon sequestration in the first half of the new century—in essence "buying time" for the development and deployment of new carbon-neutral energy technologies and infrastructure. With a solid knowledge base, biotechnology could impact terrestrial carbon sequestration in many ways, many of which were discussed in connection with biofeedstocks. Plants could be genetically modified to favor long-lived lignin in root systems. Genetic engineering also could improve the photosynthetic process itself, such as creating a more efficient Rubisco, engineering C4 metabolism and anatomy into C3 crops, and engineering symbiotic N_2-fixing bacteria into grasses.

Recognizing that most ecosystems are unmanaged lands, a central question that can be answered only with additional knowledge is "*Can technology to enhance sequestration be applied to managed lands only?*" An improved understanding of the global carbon cycle and the range of ecosystem responses to increasing atmospheric CO_2 concentrations and global warming is a prerequisite for attempting enhanced sequestration by such unmanaged ecosystems as deserts, tropical forests, savannahs, and far northern spruce forests and bogs. Fundamental knowledge still is needed to determine the requirements for sustained growth with ancillary carbon sequestration in native ecosystems. For instance, we would like to be able to predict the response of plant communities to climate change and to control losses of carbon from tundra and other ecosystems at risk from global warming.

Although the use of genetically modified plants or microbes in terrestrial ecosystems offers potentially dramatic solutions to the challenges of carbon sequestration or energy from biomass (see below), the ecological impacts and public acceptability of such a strategy also need to be thoroughly studied. Furthermore, most biotechnology solutions do not require the release of genetically modified organisms.

Ocean Carbon Sequestration: Ginger Armbrust explained the importance of fully recognizing "*the complexity and sensitive nature of the ocean systems. While the oceans represent a near limitless potential for carbon sequestration, the unknown consequences of manipulation of ocean ecosystems and their importance dictate that a vastly improved understanding precede any actions*."

Charles Kennel urged the workshop participants to "*apply biotechnology to elucidate marine processes that control global carbon cycling and climate*." With 40,000 gigatons of carbon, oceans contain 95% of the CO_2 on the planet. Each year the oceans take up about 92 gigatons from the atmosphere, returning about 90. Over the course of centuries, about 85% of the CO_2 emitted into the air by human activity and natural processes will end up in the ocean.

Unfortunately, our understanding of the processes responsible for moving carbon within and below the upper 100 meters of the ocean where photosynthetic CO_2 fixation takes place is very poor. Whereas 50% of all photosynthesis on Earth occurs in the ocean, it is accomplished by a small standing stock (~ 3 gigatons of carbon) of microscopic phytoplankton. That is less than 1% of the much larger (600-gigaton) standing biomass on land. Hence the tremendous potential of microbes for sequestering atmospheric carbon.

Ginger Armbrust explained how the "*movement and solution of CO_2 in the ocean are controlled by interactive biotic and abiotic mechanisms known, respectively, as the biological pump and the solubility pump.*" As more research on planktonic assemblages is done with more sophisticated tools, we are learning that very complex microbial webs including microalgae, protozoa, viruses, cyanobacteria, and heterotrophic and anoxygenic phototrophic bacteria control the allocation and constant reapportioning of carbon in the upper layer of the ocean. This oceanic carbon has an average turnover time between the ocean and atmosphere of one week and only about 16% is exported to the deep ocean.

Two approaches have been advanced for the sequestration of carbon in the ocean on the decadal time scale important to climate change during this century: (1) fertilization to stimulate enhanced photosynthetic uptake by phytoplankton (a strategy also amenable to biotechnology strategies) and (2) deep injection of CO_2 streams from energy production and other industrial point sources.

A critical challenge is to predict the ecological responses of the ocean's complex biological communities to these different strategies. DOE already is looking not only at the effectiveness of carbon sequestration in the ocean through iron fertilization and direct injection, but also at the environmental consequences of these approaches. DOE is supporting basic research in marine biology and ecology, as well as in biogeochemical cycling in the oceans to address this important issue.

Ed DeLong made the case that predicting the potential ecological responses of carbon sequestration requires that "*community dynamics must be understood*" and that *"biotechnology* *research can help determine community genomics and function.*" For example, environmental or community genomics approaches, such as microarrays or other high-throughput analyses, can be used to assess community gene expression under different conditions. This will increase the understanding of the photosynthetic efficiency of phytoplanktonic communities, the biological mechanisms that control the carbon cycle, the use of fertilizers by phytoplankton, and the ecological impacts of deep injection of CO_2 streams.

Understanding phytoplankton also could lead to another breakthrough. Greg Stephanopoulus suggested "*algal ponds could be a distributed solution, with thousands of ponds capturing gigatons of CO_2 at thousands of sites*." If microalgal carbon-capture productivity could reach 200 to 300 tons per hectare per year with CO_2 saturation from power plants, all of the CO_2 produced in Arizona and New Mexico, for example, could be captured in ponds that took up only 0.25% of these states' area.

Understanding the opportunities for and impacts of increasing or altering the carbon sequestration potential of the oceans or terrestrial ecosystem will be an important driver for future research and policy decisions. Today, although 50% of the earth's photosynthesis occurs in the oceans, most CO_2 in the oceans gets recycled to the atmosphere. In contrast, a larger fraction of the terrestrial CO_2 is sequestered more "permanently," in lignin-containing trees, for example. Opportunities exist, if proven safe and environmentally friendly, to dramatically increase the amount of carbon sequestered in both oceans and terrestrial ecosystems.

Important to note is that only some scenarios for the use of biotechnology in terrestrial and marine sequestration require the use of genetically modified organisms. However, processes involving the use of genetically engineered microbes will, in most cases, be contained, for example, in bioreactors. Although the use of genetically modified plants or microbes offers potentially dramatic solutions to challenges of carbon sequestration (or energy from biomass, see below), the potential ecological impacts of such a strategy would need to be thoroughly studied and assessed before any actions in the field could be taken.

Understanding The Global Carbon Cycle: Understanding the global carbon cycle is a critical part of developing new technologies to sequester carbon in marine, terrestrial, or geologic systems. These technologies must be not only technically effective, but also environmentally friendly and responsible. The relationship between global climate and the carbon cycle is complex and involves, among other things, poorly understood interactions with global cycling of iron, nitrogen, and many other elements and the hydrologic cycle at multiple spatial scales. The need for improved fundamental understanding of the carbon cycle is epitomized by the current debate over the fate, in the environment, of ever increasing CO_2 emissions. Although we know that CO_2 emissions have increased over the past few years, we don't know as yet where the extra carbon has gone. Because plants and microorganisms control carbon flow among the atmosphere, the oceans, and the land over time scales important to people, a better quantitative understanding of ecosystem function and the carbon cycle is critical. We need to know how the global ecosystem currently handles all CO_2 emissions before we try to interfere with or improve existing processes. We also need better carbon-cycle "models" to help us understand and predict the fluxes and effects of carbon on variable time scales and on global spatial scales.

The Use of Biomass for Fuel Production

- Plants can be modified to
  - grow places they wouldn't normally grow
  - grow faster and more efficiently
  - be more easily harvested
  - contain material more easily converted to clean energy

- Microbes can be used as sources of biomass for energy because they can be readily modified and will grow in industrial environments and/or inhospitable natural environments.

Biofeedstocks – Pushing the Envelope of Plant Biotechnology: To take full advantage of biomass opportunities on a global scale, "*we need a better fundamental understanding of the organisms that contain the vast majority of terrestrial biomass*." (Toby Bradshaw)

The use of biomass for the production of fuels, industrial chemicals, consumer products, and power can mitigate greenhouse gas emissions. Biomass-based systems reduce the use of fossil fuels that normally would be used and take up CO_2 through photosynthesis to make the next generation of biofeedstock materials. One industry vision of the future projects a tripling of biofeedstock use by 2020 with a continued increase to fully half of all fuel, product, and power inputs by 2050. These increases are associated with a concomitant reduction in CO_2 emissions approaching Gigaton quantities. (Remember that human activity today releases about 7.5 gigatons of carbon into the air each year.) Jae Edmonds and colleagues have suggested that even business-as-usual projections, with optimistic assumptions about research progress, only predict that by 2100 "*worldwide biomass use will be equivalent to 190 exajoules (an exajoule is 1.055 quadrillion BTUs),* ***or more than all of the oil and gas production in the world in the year 1985***." Even this level does not achieve stabilization at any concentration. The challenge is whether this rate of development can be increased so that biomass can more significantly contribute to stabilization.

For these projections to become a reality we will need a suite of biotechnology solutions, many or even most of which haven't yet been developed or even conceived. But the development and use of biotechnology feedstock solutions tailor-made to specific energy needs must always be tempered by their potential impacts on the environment, their requirement for water and fertilizer, and their productivity under varied environmental conditions.

Biotechnology research will contribute substantially to the development of many potential biotechnology feedstock solutions. These include enhancing net primary production of plants using knowledge of molecular machines and functioning of gene regulatory networks. Improvements in plant productivity could lead to more feedstock material per land area. Improving the tolerance of plants to stress also is a possibility that would extend the land base for production; for example, tolerance to drought and salinity could open up vast areas of marginal and arid lands worldwide.

Understanding the metabolism and genetics of plants and microbes and their interactions could lead to what Chris Sommerville called the "*true domestication of trees and grasses.*" This concept envisions "designer" plants genetically engineered for maximal efficiency and benefit, for example, simultaneously producing high-value chemicals in select above-ground tissues while using the bulk of the shoot material for energy and the below-ground roots for CO_2 sequestration and soil fertility. Part of this strategy would require the reengineering of the rhizosphere in the root zone to take full advantage of the various microbes that aid in plant nutrition and disease resistance. These challenges can be met only by a research program that focuses on fundamental, cross-cutting questions applicable to the biology of all living systems.

"*Why are short plants short and tall ones tall?*" With this question, Chris Sommerville reminded the group that a plant's "*life history strategy is controlled by a few genes.*" The answers are hidden in the genome. The plants most suited for feedstock production are trees and grasses, which have enormous genetic complexity. Comparing the genome of the model plant *Arabidopsis,* whose 125-megabase (Mb) haploid genome already has been sequenced, the haploid genome of the poplar is 550 Mb, switchgrass is 723 Mb, and pine is a remarkable 22,000 Mb (more than 14 times the size of the human genome)! These large genomes make the possibility of determining their complete DNA sequences greater financial and a technical challenges because of the vast repetitive stretches of DNA of unknown function.

Many important plant metabolic pathways already are well understood, but the genetic regulation of these pathways and the integration of individual metabolic pathways and regulatory networks into signaling networks within and among cells and tissues are not. We do not yet understand how a plant's most desirable characteristics needed for biofeedstocks are related to the differential allocation of the products of photosynthesis to roots, stems, leaves, and reproductive organs. Through biotechnology we can identify genetic markers that relate to allocation patterns, such as branch angle, and use them to more efficiently breed desirable characteristics. However, as important as it is, a complete understanding of the fundamental basis for the allocation of photosynthesis products throughout a plant's various tissues remains elusive.

In addition to this basic knowledge about the distribution of photosynthesis products, we need a basic understanding about how carbon is partitioned in plants, that is, the preferential translocation of photosynthesis products to other compounds important to the use of biomass including cellulose, hemicellulose, and lignin. Further, understanding the genetic control responsible for the partitioning of the various plant proteins, isoprenes, and oils will allow use of plants for manufacture of higher-value chemicals. Although this last application is not directly important to global-scale greenhouse gas mitigation, it will be an important technical bridge and financial ladder to a bio-based future energy economy.

The opportunities for developing biotechnology solutions to the challenges of global climate change will be endless when we understand the molecular biophysics that plants and an array of microbes use to harvest light. More broadly, we need to determine the genetic basis for tolerance and intolerance of plants to stress from too little or too much water and extremes in salinity, pH, and temperature.

Use of Biological Processes to Make Cleaner Fuels with Higher Energy Content

- Microbes carry out some chemical processes better than comparable solutions designed by people. Thus, microbes or their products can be used to convert sunlight, hydrocarbons, or biomass to useful energy products without the production of greenhouse gases such as CO_2. These types of biological conversions can operate under a wider range of conditions than traditional industrial approaches.

Bioconversion – Using Nature's Own Solutions: "*We need to know what biology can uniquely do that chemistry can't.*" (Martin Odom) "What are nature's schemes, and what are its limitations for bioconversion?" (Mike Himmel)

Bioconversion uses such microorganisms as bacteria and fungi or cell-free enzyme systems to capture energy or to transform organic or inorganic materials to useful products including fuel, food, fiber, and commodity and special chemicals. Bioconversion also promises innovative approaches to clean energy and for mitigating greenhouse gas emissions by directly capturing emissions from industry and power generation.

The bioconversion potential is high for a number of reasons:

- Biotechnological advances, such as genomics and proteomics, allow the identification of important reactions in microbial systems.
- Metabolic engineering can create pathways that currently do not exist.
- Natural or engineered pathways can be replicated in cells or on reactive surfaces.
- Scaling at least to the level of industrial chemicals already has been accomplished. Further scaling is doable.

Biotechnologists are not dreaming of incremental changes or improvements. Greg Stephanopoulus noted that in "*trying to amplify a pathway so it is competitive with chemical processes, . . . we don't seek to improve processes by percents; we want to increase them by factors of ten*." The challenge of developing commercially successful bioprocesses to significantly contribute to the mitigation of greenhouse gases will require a complete systems approach. Specific organisms or cell-free enzymes can be tailored to the process-system conditions and vice versa. However, even more options will be needed. Economic viability likely will demand multiple products from single or mixed feedstocks in biorefineries, just as oil refineries today produce multiple products from crude oil.

Improved understanding of the functional capabilities of microbes and natural microbial communities will lead to development of bioconversion processes yet to be conceived. Over half of all microbial genes identified to date have unknown functions. Exploiting the exquisite repertoire of diverse microbial metabolic pathways for processing carbon alone offers great potential for interconversion of methane, methanol, CO_2, CO, and derived compounds for numerous purposes, for example, methane or methanol to CO_2 and H_2. Improved knowledge of natural microbial consortia and biofilms also will lead to new industrial processes based on two or more microbial species and the engineering of pathways from two or more microbes into a single organism.

Ken Nealson emphasized the importance of "*learning to use microbes because of their smaller size, greater surface area, and higher productivity*." But the ultimate may be "*cell-free systems that perform important metabolic processes, which are decoupled from the inefficient life processes of the living system*." Revolutionary fuel cell concepts based on biology are not impossible in the future, but they require substantial fundamental knowledge of biochemical and regulatory pathways. Energy capture and use by biological systems can even be a model for innovative ways to discuss the uses of nanotechnology and new materials for greatly improved photovoltaics. Understanding how plants and autotrophic microorganisms use protein machines to split water and convert sunlight to fixed chemical energy is critical to future developments in clean energy. Simply put, "*How does a bacterium capture a photon and make it into hydrogen?*" (Ken Nealson)

A Few Cross-Cutting Challenges and Gaps in Our Knowledge

1. Biotic Interfaces – Organisms Working Together in Nature: Because individual plants, animals, and microorganisms are constantly in contact with and adjusting their behavior to the presence of others, Bob Tabita proposed that "*symbiotic partners should be jointly sequenced. For example, poplar and its mycorrhizal fungus and the bacteria endosymbiotic to both"* would be ideal targets for genomic sequencing.

From individual ecosystems to the global biosphere, we find a range of interactions at biotic interfaces mediated by microbial communities that drive the overall functioning of the systems. It is at these interfaces that key mechanisms controlling carbon and elemental cycling are believed to reside. Among the biotic interfaces critical to understanding global cycles, climate, and the influence of humankind are (1) the rhizosphere, where microbial communities interact with roots to influence the health and nutrient status of plants; (2) the "microbial loop," comprising intricate, interwoven communities of phytoplankton and bacteria controlling the ocean's biological carbon pump; and (3) microbial biofilms on all manner of mineral and other nonliving surfaces connecting the biosphere to the Earth. We need a better understanding of these complex biotic interfaces—information that will enable the development of biotechnology solutions for both carbon sequestration and energy production.

2. Energy Capture – From Plants to Microbes: Craig Venter correctly stated, "*Microbes can split water efficiently, and we can isolate that capability in engineered systems. We need to better understand microorganisms to take that next step to engineered systems*." Even small changes in biological function can have large impacts. Toby Bradshaw reminded the panel, "*A 1% increase in solar energy conversion would double crop yields*."

All energy used by life on Earth is from plant and microbial photosynthesis or from chemosynthesis—the capture of useful energy by microorganisms that mediate transformations of Fe, Mn, S, and N among their elemental oxidation states. Although about half of all photosynthesis takes place on land and the other half in the oceans, the breadth, magnitude, and importance of microbial chemosynthesis to global processes remains to be determined. New ecosystems continue to be discovered that broaden our understanding of Earth's energy systems and the opportunities for exploiting this understanding as one element of a broad biotechnology contribution to the challenges of global climate change. Discoveries over the past two decades of ubiquitous ecosystems at deep ocean thermal vents and in the deep terrestrial subsurface pose profound questions not only about the extent of life on our planet, but also about the origin of life itself and its possible presence elsewhere in our solar system.

3. Back to Basics – Metabolism and Genetic Regulation: "*Only a few genes control the life strategy in plants; . . . when we understand these, we can dramatically change plant yields.*" (Chris Somerville)

Underlying all potential applications of biotechnology to clean energy and mitigation of greenhouse gas effects on climate change is a solid understanding of the biochemistry and genetics of plants and microorganisms. And yet, we are only now beginning to appreciate the complexity of metabolic and regulatory signaling pathways in the simplest of bacteria that might be harnessed for clean energy and carbon management. If, in the long term, we are to enhance the productivity of forests, biomass crops, and agricultural systems, we must understand why, for example, the molecular machine Rubisco—a mediator of photosynthesis and the single most abundant enzyme complex on Earth—is seemingly so energetically inefficient. Could Rubisco be engineered to carry out carbon fixation more efficiently, or are there more efficient forms of this enzyme still waiting to be discovered and used? Similarly, to develop a more efficient hydrogen-based energy economy, we need to understand how oxygen poisons a key group of enzymes, hydrogenases, capable of producing H_2 in the absence of air.

Summary

The problems and challenges associated with global climate change are immense. Biotechnology can and must offer solutions. However, development of these solutions will take sustained investment in fundamental research.

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