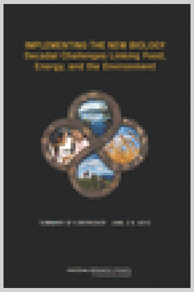

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IMPLEMENTING THE NEW BIOLOGY
Decadal Challenges Linking Food, Energy, and the Environment

SUMMARY OF A WORKSHOP JUNE 3-4, 2010

Paula Tarnapol Whitacre, Adam P. Fagen,
Jo L. Husbands, and Frances E. Sharples

Planning Committee on Achieving Research Synergies for Food/Energy/
Environment Challenges:
A Workshop to Explore the Potential of the "New Biology"

Board on Life Sciences

Division on Earth and Life Studies

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse, nor did they see the final draft of, the workshop summary before its release. Responsibility for the final content of this summary rests entirely with the authors and the National Research Council.

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1

A Vision for the Twenty-First Century: Carbon-Neutral Food and Fuel

As the second decade of the twenty-first century begins, the challenge of how to feed a growing world population and provide sustainable, affordable energy to fulfill daily needs, while also improving human health and protecting the environment, is clear and urgent.

Media headlines daily report on the impacts of climate change, economic instability, and political and social upheavals related to struggles over scarce resources. Increasing demand for food and energy is projected at the same time as the supply of land and other resources decreases. Increasing levels of greenhouse gasses alter climate, which, in turn, has life-changing implications for a broad range of plant and animal species (National Research Council, 2010a).

However, promising developments are on the horizon—scientific discoveries and technologies that have the potential to contribute practical solutions to these seemingly intractable problems. As described in the 2009 National Research Council (NRC) report *A New Biology for the 21st Century* (Box 1-1), biological research has experienced extraordinary scientific and technological advances in recent years that have allowed biologists to collect and make sense of ever more detailed observations at ever smaller time intervals. With these advances have come increasingly fruitful collaborations of biologists with scientists and engineers from other disciplines. Despite this potential, the challenge of advancing from identifying parts to defining complex systems to systems design, manipulation, and prediction is still well beyond current capabilities, and the barriers to advancement are similar at all levels from cells to ecosystems.

BOX 1-1
A New Biology for the 21st Century

A New Biology for the 21st Century is the expert consensus report authored by a committee organized by the Board on Life Sciences of the National Research Council and cosponsored by the National Institutes of Health, National Science Foundation, and U.S. Department of Energy.

The report notes how new technologies and tools are allowing biologists to move beyond the study of a single cell, genome, or organism to look broadly at whole systems and, in collaboration with other branches of science and engineering, to solve societal problems.

Through the New Biology, integration across the subdisciplines of biology, across all of science, and across agencies and institutions leads to a better understanding of biological systems in order to create biology-driven solutions to societal problems related to food, energy, the environment, and health. The knowledge and experience gained through developing and testing solutions, in turn, informs science for many purposes to predict and respond to new challenges.

To bring this new potential to fruition, biologists, in collaboration with other scientists, engineers, and mathematicians, need to fully integrate tools, concepts, and information that were previously discipline-specific to enhance understanding and to propose new ways to tackle societal challenges.

IMAGINE A WORLD . . .

Imagine a world, members of the Committee on New Biology for the 21st Century suggested in their consensus report, in which food is abundant; the environment is resilient and flourishing; energy comes from clean, renewable sources; and good health is the norm (NRC, 2009).

To reach this point, the committee called for a "New Biology" initiative that it defined as a collaborative, interdisciplinary approach to biological research to address goals that no one discipline in isolation can achieve: for example, to adapt any food plant to any growing conditions and to expand sustainable alternatives to fossil fuels. In addition, the report called for the initiative to be "an interagency effort, that it have a timeline of at least 10 years, and that its funding be in addition to current research budgets" (p. 7). Since the report's release in August 2009, committee members have presented their findings and recommendations on Capitol Hill, to federal science agencies, at the White House, and at professional meetings. The report stressed that the New Biology requires integration not only across disciplines, but also across university departments, federal agencies, and professional societies and interest groups.

The committee intended its report to serve as the first step, rather than an endpoint, in a process to determine the potential benefits and implications of the New Biology. As next steps, it envisioned a series of workshops to provide concrete examples of what New Biology research programs could look like. The first of these workshops "Implementing the New Biology: Decadal Challenges Linking Food, Energy, and the Environment," was held June 3-4, 2010, and is the subject of this summary. The Statement of Task for the Workshop is as follows:

> . . . an ad hoc committee will organize a public workshop on meeting the intertwined challenges of increasing food and energy resources in a context of environmental stress, in which participants will:
>
> - Identify a small number of concrete problems for the New Biology to solve—problems that are important and urgent (and therefore inspirational), intractable with current knowledge and technology, but perhaps solvable in a decade.
> - Identify the knowledge gaps that would need to be filled to achieve those goals.
> - Identify conceptual and technological advances essential to achieve those goals.

A GOAL AND A PATH TO GET THERE

The time was limited—less than two days. The group was diverse—about 30 researchers from different disciplines and from different institutions around the country, many of whom did not know each other previously. Yet, the workshop charge, issued by steering committee chair Keith Yamamoto, was ambitious—identify high-level, decadal-scale problems to which to direct New Biology approaches in order to increase food and energy resources in a context of environmental stress.

Steven Koonin, Under Secretary for Science in the U.S. Department of Energy, one of the workshop's four cosponsors, challenged the group to frame urgent national problems that New Biology could address. He urged that discussions aim for high level-goals that would

- Be concrete;
- Have a material impact on social problems;
- Require basic science, but not as an end in itself;
- Draw on other sciences, as well as engineering, economics, and other fields;

- Be plausible, but beyond the reach of current knowledge and technology; and
- Be quantifiable or have clear metrics to determine success.

The participants took up the challenge. In a series of breakout and plenary sessions, they grasped the need for and potential impact of a large goal to energize the public, stimulate new scientific discovery, and motivate a new generation of students. The workshop's focus on food, energy, and the environment led to the identification of a goal that, when solved, could meet the world's growing demand for food; reduce the environmental impacts of fertilizers, pesticides, and water to produce food in sufficient quantity and quality; and lessen dependence on greenhouse gas-producing fossil fuels.

Overarching vision: Achieve carbon neutrality in the agriculture and biofuel sectors.

- This broad goal was enunciated in various ways throughout the workshop: "Carbon-neutral food and fuel"; "Carbon-neutral nation"; "Get carbon from the air rather than from the ground"; "Build a carbon-neutral healthy food supply while doubling food production, providing the national liquid fuel supply, and engineering crop plants to adapt to climate change."
- Participants noted that carbon neutrality—that is, balancing the level of carbon released and sequestered as a result of food and fuel production and utilization—is a goal that meets each of the criteria proposed by Dr. Koonin. It is concrete, is measurable, and would have great significance (Box 1-2).
- Participants emphasized that reaching carbon neutrality in food and biofuel production will demand fundamental research, technology development, and engagement of diverse stakeholders (Figure 1-1) to make advances that, at this time, can barely be described, much less executed.

Workshop participants stressed that the urgency and importance of this goal will engage policy makers and the public. Three reasons to adopt an ambitious goal were identified:

1. It is essential and urgent, now and for future generations, to take on these challenges, given projections about population and resource availability.
2. The New Biology provides a route to new scientific discoveries and technological advances that address these major societal challenges.

BOX 1-2
Carbon Neutrality: Why Aim for It?

Greenhouse gases (GHGs)—carbon dioxide, methane, nitrous oxide, and other chemical compounds—are natural components of the Earth's atmosphere, but since large-scale industrialization began about 150 years ago, atmospheric levels of greenhouse gases have increased 25 percent. Moreover, the last few decades have seen the largest rise, with carbon dioxide emissions projected to increase 1.8 percent each year between 2004 and 2030.

Rising concentrations of GHGs have already increased the Earth's average temperature about 0.8 degree celsius in the last 30 years. Climate change affects not only temperatures at the Earth's surface, but also precipitation patterns, storm severity, and sea level. Effects on growing seasons, public health, animal survival, and many additional impacts will follow.

Carbon dioxide is by far the most abundant greenhouse gas. In the United States, fossil fuels supply 85 percent of our energy and produce 98 percent of our CO_2 emissions. Human activities also produce other GHGs, including methane and nitrous oxide, in excess of pre-industrial levels.

Conversely, biological systems can sequester greenhouse gasses in biomass and soils, reducing the amount released into the atmosphere.

The challenge: find ways to reduce the amount of greenhouse gases released into the atmosphere by increasing the amounts that are sequestered while also fulfilling transportation, food, and other needs.

SOURCE: U.S. Energy Information Administration (http://www.eia.doe.gov/environment.html).

3. A bio-economy, based on renewable and alternative energy sources rather than fossil fuels, is ambitious, but attainable with coordinated public and private sector commitment.

Workshop participants noted that the magnitude of the problem and the challenges to solve it will inspire the scientific community, especially if the federal government commits to long-term support. Three themes emerged from the workshop discussions:

1. Five broad scientific deliverables, each of which would be achievable through a coordinated New Biology approach:

- Measure carbon flow quantitatively, defining fully its movement through production and use systems;

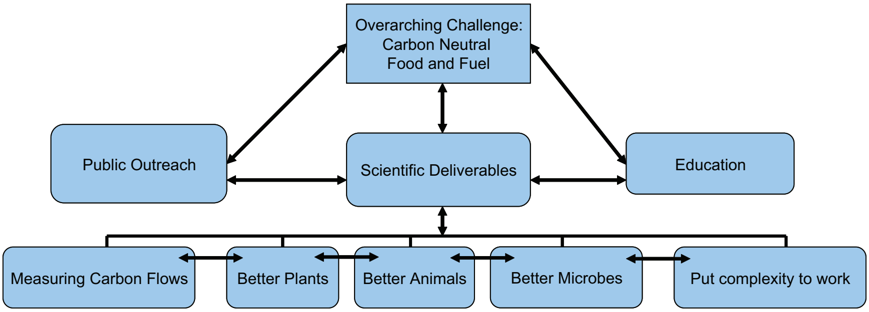

FIGURE 1-1 Achieving carbon-neutral food and biofuel through the New Biology will require public outreach, coordinated scientific and technological investment, and a commitment to innovative educational approaches.

- Optimize plant productivity to improve yield;
- Improve both the efficiency of animal production and the management of animal waste;
- Develop biofuel feedstocks that prosper in diverse, local environments, especially on land not currently suitable for food production; and
- Understand and exploit complex biological systems, from microbes through ecosystems, to improve the sustainability of food and energy crop production.

New Biology approaches to pursue these deliverables are summarized in the next section.

2. New fundamental knowledge about plants, microbial communities, and larger complex biological systems is needed to fulfill these deliverables, but acquiring this knowledge is not an end in itself. Maintaining focus on achieving carbon neutrality will provide direction and target technological and basic knowledge breakthroughs to enable the research to contribute directly to societal needs. Breakthroughs achieved in pursuit of carbon neutrality can be expected to yield other benefits, as did other ambitious, future-directed goals such as landing a man on the moon and sequencing the human genome.

3. Concrete plans and organizational structures across agencies and institutions could provide long-term coordinated support to leverage the scientific effort.

Workshop participants noted that a goal linked to compelling scientific challenges will inspire the nation's top students to pursue scientific careers**.** Three imperatives emerged:

1. Biologists, physical scientists, computational scientists, engineers, and their students will *want to* pursue the exciting possibilities of New Biology.
2. The educational system, K-12 through graduate school and beyond, will need to prepare aspiring "New Biologists" of the future to engage in hands-on discovery, equipping them with the math and computational skills that scientific research increasingly demands, and teaching them to collaborate with peers.
3. No one person will be an expert in all that the New Biology encompasses to achieve carbon neutrality or any other goal. Rather, New Biology programs will require a diverse collection of experts who define and work toward ambitious goals in multidisciplinary teams.

Workshop steering committee Chair Keith Yamamoto captured the spirit and potential benefits of setting an inspiring goal such as achieving carbon-neutral food and fuel by reminding participants that no one knew how to land a man on the moon or sequence the human genome when those goals were first stated. Similarly, although no one had drawn out specific battle lines when the war on cancer was declared and although we have not yet "won" that war, we have made remarkable discoveries and progress toward cures during its pursuit. In each of these cases, enunciation of the challenge itself provided focus and inspiration, and provided impetus to drive the development of new technologies that produced profound advances. He predicted that a similar level of scientific dedication and commitment can, with the appropriate investments, provide food and biofuel in an environmentally sound manner in the twenty-first century.

2

Developing the Vision: Highlights of the Workshop

On June 3-4, 2010, a steering committee working under the auspices of the National Research Council's (NRC's) Board on Life Sciences (BLS) convened the workshop "Implementing the New Biology: Decadal Challenges Linking Food, Energy, and the Environment" in collaboration with the U.S. Department of Energy (DOE), U.S. Department of Agriculture (USDA), Howard Hughes Medical Institute (HHMI), and Gordon and Betty Moore Foundation. All of these entities supported the workshop, which was held on the HHMI campus in Chevy Chase, Maryland. It is evidence of the compelling nature of the New Biology concept, and of the interdependence of the four challenge areas put forth in the New Biology report, that an organization dedicated to *biomedical* research and education hosted a workshop focused on food, energy, and the environment.

In welcoming participants, HHMI President Robert Tjian invited them to consider the HHMI campus as a place to come together to think about applying the New Biology to national, and even global, problems. The steering committee, led by Keith Yamamoto, chair of the NRC Board on Life Sciences, developed an agenda to do just that. (See Appendix A for brief biographies of steering group members.) In two days of breakout and plenary sessions, the workshop participants were asked to identify high-level goals to engage a range of stakeholders, including policy makers, scientific and technical communities, and students. (See Appendix B for the workshop statement of task, agenda, and list of participants.)

Describing the promise of the New Biology, Dr. Yamamoto said, "We have reached a point in our research that we have begun to appreciate the remarkable complexity of biological processes that we could not have appreciated when studying one gene and one gene product at a time. While that is daunting and scary, it is those same discoveries that have given us a shadowy view of our way through. If we can work our way through, if we succeed and integrate, the knowledge that is discovered can be used to effectively address and solve vexing, urgent, social problems."

INITIAL IDEAS TO SPARK DISCUSSION

The workshop steering committee asked each participant to arrive prepared to make a three-minute presentation of a "big idea," an idea out of reach of a single discipline or a single funding agency but something that, if achieved, would advance two or all three of the challenge areas.

Some participants began with straightforward observations. For example, Don Ort noted that crop yields, even in record years, do not reach their theoretical potential. "I'd like to see research to raise record yields toward the theoretical and even to raise the theoretical," he said. Several speakers took note of how some plants can survive in inhospitable environments, such as semiarid environments, salt water, or places as mundane as a crack in a sidewalk. Understanding how plants grow under highly unfavorable temperature, water, and nutrient conditions could enable development of crop plants that thrive in areas where malnourishment and starvation are acute and contribute to the ability to develop biofuel feedstocks that compete minimally with food crops or impact natural ecosystems. Greg Stephanopoulos also highlighted the importance of algae as feedstocks in the future. Their rapid growth and consequent high productivity make them a potentially unlimited source for biofuel and other purposes, he said, if we can develop the technology to grow and harness them in a viable way.

Expanding on this same theme, Richard Flavell proposed closer coordination between synthetic biologists and plant breeders to create new plant forms with desirable traits, such as drought tolerance, and to move this knowledge from scientific journals to production in the field. Presenters also noted that creation of diverse new plants requires that we first do the science to provide a deep and detailed understanding of a single species—something that sounds deceptively simple, yet is anything but. "We need to understand how one plant works in great detail to be generalizable to others," said Jeffery Dangl. For this reason, a number of speakers decried the declining federal support for basic research on *Arabidopsis* as a model plant species as "misguided."

To Ann Reid, new knowledge about microbes is essential to understand and be able to exploit their roles in improving plant growth and productivity. Currently, how microbes perceive their surroundings and interact with each other and with plants in the environment around them is mostly unknown. She and other presenters said that deeper understanding of microbes, their functions, and their interactions is essential to meet the goals set out in the New Biology report. Charles Rice went further and suggested that understanding and manipulating plant-associated microorganisms could make plants "self-fertilizing" and thereby reduce the need for nitrogen and phosphorus fertilizers, which are a major component of fossil fuel inputs in crop production (Box 2-1).

Some presenters carried the theme of exploiting complexity over to the ecosystem level. Rebecca Nelson, for example, noted that although current agricultural systems are productive, they depend on intensive fossil fuel inputs, which produce unwanted environmental problems. She suggested that optimizing complex plant-soil-microbe interactions would be a superior approach for managing agroecosystems. "Build agriculture based on optimized complexity, rather than optimized simplicity," she urged. This would have to happen over time and would need to rely on the practical observations and experiences of farmers with first-hand insights into crop growth as well as the scientists who study these complex systems.

Such examples illustrate some of the ideas in these short presenta-

BOX 2-1
Fossil Energy Inputs in the Current U.S. Food Production System

According to Pimentel et al. (2008), production, transportation, and preparation of the U.S. food supply are driven almost entirely by nonrenewable energy sources. In total, about 19 percent of total energy use in the United States is accounted for by the production, processing and packaging, transportation, and preparation of food. In the production of corn, one of the major U.S. crops, fossil fuel energy is consumed in eight major input categories (in decreasing order of importance): nitrogen fertilizers; irrigation; gas and diesel fuel; machinery (including energy costs of manufacturing); drying of harvested crop; seed production; phosphorus fertilizers; and herbicides. A 2010 NRC (NRC, 2010b) report noted that although the estimated value of U.S. farm income increased by 31 percent since 1970, the aggregate value of net income to farmers has not changed much in the last 40 years. In 2008, U.S. farms sold $324 billion in agricultural products but incurred $291 billion in production expenses, including $204 billion for purchased inputs. Much of the recent increase in purchased input costs was related to the rising costs of fuel and synthetic fertilizer, given that crude oil rose from $12 per barrel in 1998 to $95 per barrel in 2008. In 2007, only 47 percent of all U.S. farms reported positive net income, down from 57 percent in 1987.

tions, which addressed systems at all scales from microbes to whole ecosystems. They touched on issues that are complex, highly useful to humans, yet currently unsolvable, and laid the groundwork to think through big goals and the research needed to reach these goals.

IDENTIFYING A HIGH-LEVEL GOAL

The steering committee assigned participants to three breakout groups to ensure that each included a diversity of expertise. These diverse groups independently converged on a single problem focus: how New Biology can lead to new methods of agricultural and biomass production that, in turn, can reduce the amount of carbon dioxide released into the atmosphere and achieve carbon-neutral food and biofuel.

Breakout Highlights

Each group came to this common focus from a different, but complementary, perspective. Group 1, for example, discussed the spillover benefits that will accrue through finding new ways to produce food and biofuels. As Julie Theriot, the spokesperson for Group 1, said, "One dollar invested in agriculture is one dollar invested in health, food, energy, and environment, as investments in agriculture are leveraged across these multiple areas."

Christopher Somerville, representing Group 2, said the "banner goal" of seeking to achieve carbon-neutral food and fuel requires deeper understanding of three broad areas:

1. *How plants operate*. It is commonly observed that some plants have record yields in certain years; a mechanistic understanding of this phenomenon could be used so that plants function at optimal efficiency more consistently.
2. *How microbes function*. Microbes pose many unknowns, yet they are "the endless, limitless, renewable resource" that could be tapped to help achieve carbon neutrality, for example, through reduced pesticide usage.
3. *How to optimize biocomplexity for more efficient, environmentally benign agriculture*. This includes, for example, recognizing the role of microbial and insect communities in sustaining plant and animal health and determining how to plant mixed crops to minimize fertilizer and water requirements and maximize pest and disease resistance.

Sean Eddy, reporting on behalf of Group 3, said the funding gap in basic plant research means that strengthening a broad knowledge base is a prerequisite to achieving carbon neutrality. However, a basic-research goal in itself is "not good enough to attract the motivation, mindshare, and attention" of stakeholders; rather, basic research must relate to societal needs. The group discussed a "Plan A" and a "Plan B": Plan A to achieve a carbon-neutral environment; if not, Plan B to learn how to adapt to a non-carbon-neutral environment and to accelerate the time scale of that adaptation.

TRANSFORMATIVE IMPLICATIONS

Discussion ensued about whether the public would embrace the goal of carbon neutrality as being as clear as "landing a man on the moon." Various participants affirmed that the advances implicit in this goal would, indeed, require transformative discoveries to produce new knowledge. The significance of and need for these advances, as well as the consequences of not tackling them, would have to be explained to the public.

- **The world needs answers**. We are heading toward a "perfect storm," asserted Steven Kay, in which population growth, climate change, and diminishing oil supplies will collide. He called for "HOLI"—high-output, low-input—agriculture. While previous flagship reports have touched on many of the issues under discussion, what is different here is the opportunity to mobilize the information in pursuit of a goal that "raises [goose] bumps on your arms."
- **Carbon neutrality and other environment-related goals have a human dimension**. "We need to construct a nutritious and culturally acceptable diet that 9 billion people can consume and that advances their health, and produce it in ways that are sparing of the environment, "said Jeffrey Gordon. "All sorts of complexities are involved in solving a problem like that."
- **Integration of disparate systems represents a huge departure from business as usual**. The many different areas discussed in the breakout and plenary sessions represent state-of-the-art research in their own right, but what is remarkably different from business as usual is integrating all those novel systems, said Dr. Flavell. "We shouldn't fall into the trap of forgetting the progressive challenges that need to be invented—and forget the enormous challenge and excitement of integration," he said.
- **Carbon-neutral agriculture could, in theory, occur today—but not in reality, because doing so would not meet current food demand**, said Martha Schlicher. Providing carbon-neutral food while also substantially increasing food production, as population growth estimates dictate, fur-

ther compounds the challenge—but also provides even more urgency to address it.

DRILLING DOWN

Subsequent breakout sessions discussed priorities and further described the activities necessary to achieve carbon neutrality.

Research for Improved Outcomes

Dr. Theriot's Group 1 discussed what it termed "agro-ecosystems engineering" to achieve carbon-neutral food and lower-carbon energy sources in less than two decades. Envisioned outcomes include higher-yielding crops and cropping systems, as well as integrated land use, improved natural resource utilization and stewardship, better nutrition and health, and understanding of the interconnections between food and energy sources. Achieving these outcomes will require that research be performed and integrated as a continual feedback loop, encompassing

- *Observational research* of the characteristics of existing systems, including phenotypic (remote and in situ sensing, physical architecture) and genotypic analysis;
- *Experimental work*, including advanced crop breeding, synthetic biology, and molecular techniques;
- A *database* that integrates the observational and experimental work and helps develop iterative hypotheses that can be tested in experiments and confirmed by observations of systems—a database to handle and organize such voluminous data implies that advances in data gathering and bioinformatics infrastructure are necessary; and
- The development of *social policy goals*: engagement of stakeholders, especially farmers doing the agricultural work, as well as legal, ethical, and educational implications.

Breakout Group 2 discussed similar themes related to outcomes and research. A critical first step, as reported by Dr. Somerville and described later in this summary, is to determine how to measure carbon flow comprehensively and to quantify carbon flux in agriculture. Also stressed was the recognition that carbon-neutral agriculture goes far beyond plants to involve animals and bioenergy. Group 2 also made the point that the measurement of carbon fluxes is a classic example of a goal that requires interagency coordination, because many agencies (DOE, USDA, etc.) are involved in ecosystem and greenhouse gas monitoring and a major goal of a New Biology initiative would be to ensure coordination of these efforts.

Carbon from the Air, Not the Ground

In summarizing the highlights of Group 3, Dr. Eddy said that members found the goal "to get carbon from the air rather than from the ground" a compelling concept of what New Biology can do, particularly in terms of advances in synthetic biology and engineering. These techniques have emerged as part of an evolving field, but he said there seems to be an inflection point in studying and applying them, as well as great enthusiasm among the new generation of students.

This group, he said, crafted a statement that captures the intent to build a science and technology base to solve a range of problems: *engineering plant performance for a changing environment to better serve a bio-based economy.* He singled out key terms in the statement: (1) *engineering*: this is an applied science; (2) *changing environment*: climate change will require new plants that are adaptable to new realities; and (3) *bio-based economy*: getting carbon from the air, not from the ground, and moving away from fossil fuels toward using biomass for energy and materials.

ENGAGING SCIENTISTS: FIVE BROAD DELIVERABLES

Ultimately, workshop participants identified five broad deliverables that together could move food and bioenergy production toward carbon neutrality, as well as examples of activities and potential organizational structures to accomplish them. The groups suggested important paths for exploration, leaving it to the imagination and creativity of the scientific community to identify the enabling technologies and detailed approaches.

Figure 2-1 illustrates the connections among the pieces discussed throughout the workshop:

- An overarching challenge to use the New Biology to produce carbon-neutral food and fuel;
- Engagement of diverse stakeholders, each with different perspectives and priorities; and
- For the scientific and technical community, suggestions of the kinds of interdisciplinary, pioneering research to achieve this overall challenge.

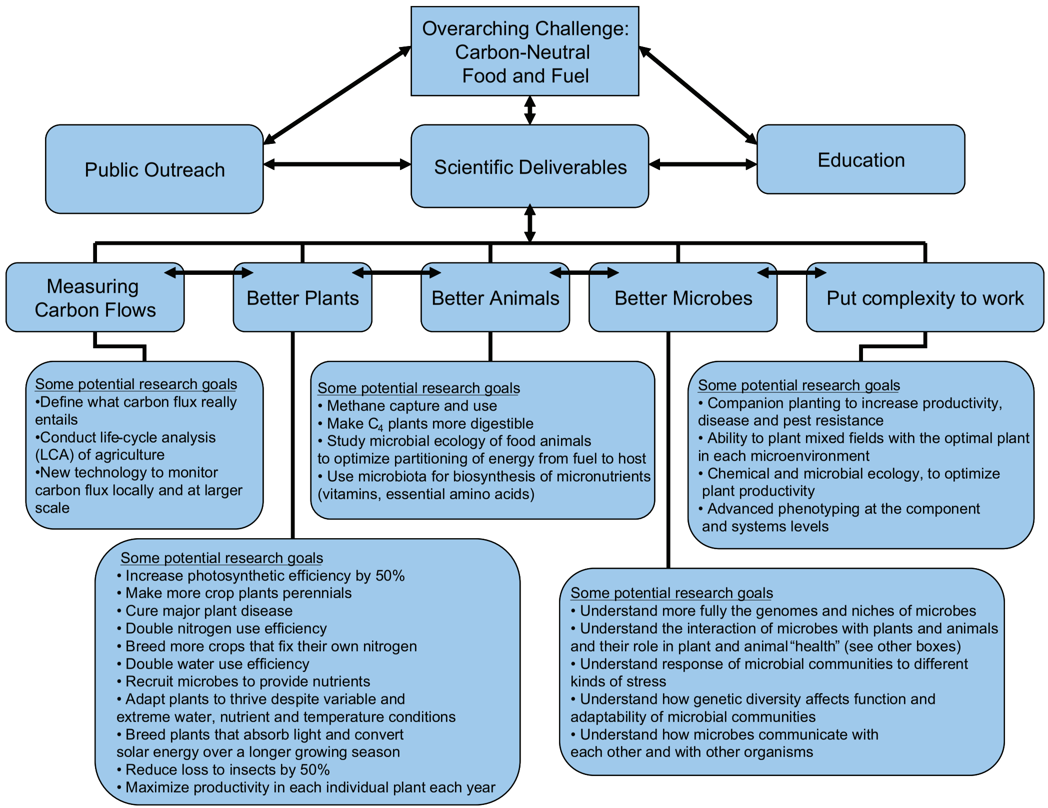

FIGURE 2-1 Components identified by workshop participants to achieve carbon-neutral food and biofuel.

Measuring Carbon Flows

To achieve carbon neutrality, we must determine quantitatively how carbon enters the atmosphere and how it is stored and released, said Dr. Somerville. This understanding is essential for rational design of strategies with the greatest impact and for effective monitoring. Such a "life-cycle analysis" (LCA) would require a multidisciplinary research effort that includes the following:

- Defining what carbon flux related to agriculture really entails
- Conducting a life-cycle analysis of agriculture
- Integrating data in a central point, fed by collaborators in different ecosystems
- Developing science-based rule-making and policy based on the findings

According to Somerville, this type of research suggests the need for a center, perhaps in a hub-and-spoke configuration with assignable responsibilities and accountability against the goals. The DOE, at Argonne National Laboratory, is now taking on a piece of this large project.

Optimizing Plant Productivity

Dr. Ort suggested that New Biology integration of expertise is required to

- Increase photosynthetic efficiency by 50 percent;
- Reduce damage from plant disease, which could increase yield by 30 percent and also save water;
- Double nitrogen use efficiency and increase the number of nitrogen-fixing crops;
- Double water use efficiency;
- Improve nutrient acquisition through novel microbial associations;
- Optimize CO_2 response in plants and increase plant tolerance to changing precipitation patterns, extremes in growing conditions, and tropospheric ozone;
- Decrease the time required for plants to mature so they can be productive in shorter growing seasons;
- Develop new perennial crop and biofuel plants, introduce perenniality into annual plants, and develop multiple cropping capabilities;
- Reduce loss to insects by 50 percent; and
- Maximize productivity in each individual plant, each year.

Group participants discussed three organizational models that might be considered to accomplish this work: a terragrid (deployed centers across the country that are available to grow and test crops, making the technology accessible to researchers at smaller and nontraditional institutions); centers (both program-project and hub and spoke); and small investigator teams that include people from different disciplines. DOE and the National Science Foundation (NSF) may be most involved in basic discovery, with USDA involvement down the line for implementation.

Improving Animal Health and Waste Management

Workshop participants recognized that the production of meat from ruminants is the single largest use of land as well as a major source of greenhouse gas (GHG) emissions. The development of improved systems for producing animal protein was, therefore, seen as an important objective; improved animal health and waste management were seen as having the potential to increase efficiency and reduce pollution from animal agriculture.

Workshop participants suggested research activities in the following areas:

- Developing livestock and husbandry procedures that do not employ antibiotic therapy
- Developing feedstocks that are digested more efficiently
- Improving energy partitioning between feed and the host—potential approaches include manipulation of microbiota by pre- or probiotics, genetic engineering of metabolic traits in microbial communities, genetic manipulation of animals and exploitation of wild alleles for energy utilization, and plant manipulations to optimize feedstocks
- Increasing energy conversion in food source animals—domesticate high-energy conversion efficiency animals for food sources
- Minimizing animal efflux or using it for energy
- Improving containment of microbes, such as enteropathogens, to keep them out of the food and water supply—develop sensitive biosentinels to ensure that standards are met

Microbes will play an essential role in improved animal husbandry and waste management. For example, ruminant microbiota within the cow gut break down cellulosic material, which could be more thoroughly explored for wider application. Participants suggested that the New Biology can help us understand how to maximize nutrient flow, creating a cow that is healthier for the human diet and changing the microbial ecology of the cow (and perhaps other animals) to optimize partitioning of energy from fuel to host and of meat production for human food; understand and perhaps exploit the end products of fermentation in the cow rumen; and understand the nutritional and other consequences of altering gut microbial ecosystems.

Workshop participants suggested that the U.S. Department of Agriculture's National Institute of Food and Agriculture could serve as the lead agency in this work, but other agencies that are highly relevant include the Food and Drug Administration (FDA; for antibiotic issues), the National Institute of Diabetes and Digestive and Kidney Diseases (nutrition and microbiome), DOE (energy capture and methane utilization), and the Centers for Disease Control and Prevention (enteropathogens and other microbes dangerous to human health).

New Feedstocks for Biofuel in New Environments

Developing feedstocks that prosper in diverse, local environments could allow the United States to be self-sufficient in liquid fuels, said Steven Long.

Although estimates differ widely, Dr. Long said that as much as 200 million hectares of abandoned agricultural land may be available in the United States. This land, such as overgrazed pastureland in the Southwest, often has road access or some infrastructure in place. He said that a critical precursor is a coherent database of such areas, along with their biodiversity, ecosystem services provided, soils, and climate now and over the next 30 years. Some of the information exists but is scattered; other data need to be collected.

Potential new feedstocks encompass two broad classes of crops: (1) emergent crops that have already been used in some form and (2) potential crops that have not been tested to any level.

Emergent crops: Expand exploration of *Saccharinae* (sugar cane, energy cane, miscanes, *Miscanthus*, sorghums) and *Pennisetum* and switchgrass for further testing and to build up national germplasm collections. Workshop participants suggested the following research on crops to advance their emergence as new biofuel feedstock:

- Identification of potential pests and diseases, eliminating plant strains that are highly vulnerable to catastrophic diseases, or developing management options or disease resistance;
- Stimulation of regionally appropriate public sector breeding or propagation systems that reduce risk for the private sector at the initial stages;

- Genome sequencing and development of molecular marker technologies, selection criteria, and rapid phenotyping, using high-throughput technologies;
- Developing strategies to exploit management and biotechnology of nitrogen fixer-mycorrhizal associations;
- Developing effective genetic transformation technologies for these emergent crops;
- Developing algorithms to derive mechanistic models to predict yield maps in the absence of historical datasets;
- Creating a network of GHG balance measurements for emerging feedstocks; and
- Developing predictive engineering and systems analyses, as well as life-cycle and economic analyses.

Potential feedstocks: Develop *Agave* and *Opuntia* for semiarid environments and mangrove and cordgrass for saline environments.

Understanding and Exploiting Complex Biological Systems

Throughout the workshop, participants observed that current agricultural systems are based on optimizing *simplicity*—for example, through monoculture. In contrast, *taking advantage of the complexity characterizing natural biological systems*, from microbes through ecosystems, could increase productivity and sustainability.

Dr. Nelson listed criteria to determine whether qualitative and quantitative productivity is maintained or increased through optimizing complexity, such as efficiency of resource use, resilience and stability with regard to climate and pest and disease challenges, and reduction in externalities (i.e., forms of pollution).

In addition to many components included in previous deliverables, participants suggested research activities in the following areas:

- Functional diversity, to manage pests and diseases, improve water and nutrient use, and overall to better manage risk over time;
- Optimized biocomplexity—companion planting to increase productivity, disease and pest resistance, and the ability to plant mixed fields with the optimal plant in each microenvironment;
- Chemical ecology, to learn how plant biochemistry can be used to help crops compete more effectively with weeds and optimize beneficial interactions with insects; and
- Advanced phenotyping at the component and systems levels, remotely and in situ.

Dr. Nelson pointed out that organizationally, the work is inherently distributed because each system is so particular, although data handling, modeling, and remote sensing could be centralized. Individual and small groups would use the data, and individual farmers can also be involved. She suggested that USDA could be the lead agency for this research, backed up by DOE and NSF.

ENGAGING THE NEXT GENERATION: EDUCATION FOR THE NEW BIOLOGIST

The New Biology will require the talents of appropriately educated New Biologists, prepared to train others to pursue challenges described throughout the workshop.

Broadening Education Offerings

The New Biologist, said Gary Stacey in his report on breakout group discussions, will be conversant in math and computational science and able to interact effectively with a broad pool of collaborators—chemists, physicists, engineers, computer scientists, and many others—people challenged and inspired to solve New Biology-related problems from their different perspectives and types of expertise. Workshop participants reiterated the importance of supporting the kinds of changes in education practices that were outlined in the New Biology report. Existing programs, such as those sponsored by HHMI and NSF's IGERT program[1] could be used as models for incorporating educational goals into the program to achieve carbon neutrality.

Increased support could be used to fund pilot projects around the country in which universities work with local K-12 school districts, especially students in grades 4-6, where their early interest in science is often either fixed or lost. Universities could also work within their colleges of education to reach K-12 educators who then reach their students. Workshop participants referred to the work of Dr. Jo Handelsman for valuable input about programs. The key is sustained commitment that has measurable impact on what students and teachers learn beyond the occasional short course or institute.

Strengthening the Bioinformatics Infrastructure

Many of the participants expressed the conviction that a coordinated approach to information, bioinformatics, analysis, and data sharing is

[1] Integrative Graduate Education and Research Traineeship. See *http://www.nsf.gov/crssprgm/igert/intro.jsp* and *http://www.igert.org/* for more information.

critical to reaching the carbon neutrality goal. Bioinformatics is a critical enabling technology, said Dr. Eddy on behalf of his breakout group, and he called for comprehensive and robust programs and databases to address a variety of needs beyond gene sequence information. New Biologists can be educated to use bioinformatics themselves, rather than rely on separate informatics experts for assistance. As an analogy, molecular cloning was a separate discipline in the 1970s but is now a procedure that all biologists use as needed. Similarly, biologists should be able to program with simple computer languages, at least for their needs to design experiments and analyze data, without having to become software or hardware experts.

Eddy pointed out that it is important to avoid overdesigning systems, especially in rapidly advancing areas, so that they try to accomplish too much and therefore are not good for anything in particular. Avoid "building superhighways before we know where the traffic is going," he urged. Instead, employ simpler systems, at least initially, not necessarily *integrated* out of the box but "*integrate-able*."

Eddy suggested that computer simulations, carefully done, can contribute critical advances across the range of investigations considered in this summary; this kind of problem-based learning could entice computer and other technical people to be drawn to biological issues.

ENGAGING THE PUBLIC AND POLICY MAKERS: DIAGNOSES AND CURES

Achieving carbon neutrality calls for involvement by many stakeholders, not only in science and education, but also those who make funding decisions, develop policy, and give or withdraw public support through advocacy and voting. These stakeholders would respond to a properly enunciated "diagnosis" of the problems and to potential "cures" that the New Biology could contribute, according to Dr. Theriot, reporting from the breakout session.

Dr. Theriot pointed out that "diagnoses" include documented information about current and future food and resource shortfalls, as well as projections about U.S. economic and agricultural performance (Box 2-2). In contrast, "cures" will involve challenging technological and conceptual advances, integration across fields, and partnerships with industry:

- Doubling food and bioenergy production;
- Transforming *what* we eat and *how* it is produced;
- Developing socially acceptable, economically viable, and environmentally sustainable solutions;

- Producing biomass for fuel without competing with food production; and
- Building a bio-economy through development of a sustainable biofuel and green chemical industry, new bioproduction systems, new materials, and development of biogas.

BOX 2-2
Diagnosis: Why the Urgency?

These data were presented during the Group 1 breakout session in slides from David Rice, Kansas State University:

- Worldwide, 854 million people are chronically malnourished, 2 billion people suffer from hidden hunger, and one-half of childhood deaths are attributable to malnutrition.
- Increased population (9 billion globally) and changes in lifestyles will require that food production substantially (e.g., by 50 percent or more) increases by 2050.
- Production systems will become increasingly dependent on inputs of fertilizers, pesticides, and water, under current trends.
- In 50 years, an 18 percent increase in agricultural land area will result in a significant loss of land area for natural ecosystems with attendant impacts on biodiversity.
- The United States spends $750 million every day to import fuel.
- Current policies create artificial competition between food and energy.
- U.S. preeminence in agriculture is based on an unsustainable model.

Conversely, advances in food and bioenergy production that are socially acceptable, economically viable, and environmentally sustainable can be within reach through integration across fields of science and technology.

3

Wrap-up and Next Steps

The workshop was not designed to end with final consensus or recommendations, and none are given here. However, certain points of discussion resonated with participants:

- New Biology can help achieve carbon neutrality in food and biofuel. Discussion throughout the workshop centered on impact, projected time lines, and the many different aspects of science and technology to be integrated and focused.
- Basic, foundational research in plant science has many gaps that need to be filled to achieve carbon neutrality as well as the many other plant improvements discussed. By focusing on the kinds of societal needs discussed here, this research could inspire the necessary support and enabling technologies essential for meeting the challenges.
- Different approaches will be necessary to engage stakeholders with very different perspectives, areas of expertise, and needs in these issues. The public and policy makers may respond best to projected problems related to food, energy, the environment, and health, and how New Biology approaches can lead to cures. Diverse scientific communities need to be inspired and excited about the research to find solutions. If the "top talents" of the future—whether they become biologists, physicists, computational scientists, or other experts—are inspired through public outreach and educational opportunities, they, too, will join in the pursuit.

As Dr. Yamamoto thanked the group for participating in this "first experiment" of workshops, he said its work will stimulate activity to use New Biology to solve the challenges that the world, and the United States in particular, face related to food, energy, and the environment.

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Appendix A

Workshop Steering Group

Keith Yamamoto, Ph.D. (NAS/IOM), *chair*, is professor of cellular and molecular pharmacology and executive vice dean of the School of Medicine at the University of California, San Francisco (UCSF). He has been a member of the UCSF faculty since 1976, serving as director of the Program in Biomedical Science's (PIBS) Graduate Program in Biochemistry and Molecular Biology (1988-2003), vice chair of the Department of Biochemistry and Biophysics (1985-1994), chair of the Department of Cellular and Molecular Pharmacology (1994-2003), and vice dean for research, School of Medicine (2002-2003). Dr. Yamamoto's research is focused on signaling and transcriptional regulation by intracellular receptors, which mediate the actions of several classes of essential hormones and cellular signals; he uses both mechanistic and systems approaches to pursue these problems in pure molecules, cells, and whole organisms. Dr. Yamamoto was a founding editor of *Molecular Biology of the Cell* and serves on numerous editorial boards, scientific advisory boards, and national committees focused on public and scientific policy, public understanding and support of biological research, and science education; he has served on the Coalition for the Life Sciences (formerly the Joint Steering Committee for Public Policy) since 1996. For the National Academy of Sciences, he chairs the Board on Life Sciences. Dr. Yamamoto has long been involved in the process of peer review and the policies that govern it at the National Institutes of Health (NIH), serving as chair of the Molecular Biology Study Section, member of the NIH Director's Working Group on the Division of Research Grants, chair of the Advisory Committee to the NIH Center for Scientific Review (CSR), member of the NIH Director's Peer Review Oversight Group, member of the CSR Panel on Scientific Boundaries for Review, member of the Advisory Committee to the NIH Director, co-chair of the Working Group to Enhance NIH Peer Review, and co-chair of the Review Committee for the Transformational R01 Award. Dr. Yamamoto was elected as a member of the American Academy of Arts and Sciences in 1988, the National Academy of Sciences in 1989, the Institute of Medicine in 2003, and a fellow of the American Association for the Advancement of Sciences in 2002.

Vicki L. Chandler, Ph.D. (NAS) is the chief program officer for science at the Gordon & Betty Moore Foundation in Palo Alto, California. She also maintains an active research program at the University of Arizona-Tucson, where she is a Regents' Professor in the Departments of Plant Sciences and Molecular and Cellular Biology and a member of the BIO5 Institute. She holds the Carl E. and Patricia Weiler Endowed Chair for Excellence in Agriculture and Life Sciences. Dr. Chandler received her B.A. from the University of California, Berkeley, and her Ph.D. from the University of California, San Francisco. She has conducted pioneering research on the control of gene expression in plants and animals. She has received numerous honors and awards including a Presidential Young Investigator Award, Searle Scholar Award, the National Science Foundation (NSF) Faculty Award for Women Scientists and Engineers, and the NIH Director's Pioneer Award. She was elected to the National Academy of Sciences in 2002. She has served extensively on national advisory boards and panels for NSF, the Department of Energy (DOE), NIH, and the Howard Hughes Medical Institute (HHMI). She served on the NSF Biological Directorate Advisory Committee from 2001to 2004 and served on the National Research Council (NRC) Committee on Defining and Advancing the Conceptual Basis of Biological Science. She has chaired or co-chaired national conferences for Keystone, the Federation of American Societies for Experimental Biology (FASEB), and the Gordon Research Conference (GRC), serving on the GRC board of trustees, and in 2001 as chair of the board. Dr. Chandler was elected to the International Society of Plant Molecular Biology Board of Directors 1999-2003 and elected president of the American Society of Plant Biologists for 2002. In 2007 she was elected to the Council of the National Academy of Sciences.

Christopher B. Field, Ph.D. (NAS) is the founding director of the Carnegie Institution's Department of Global Ecology, professor of biological sciences at Stanford University, and faculty director of Stanford's Jasper Ridge Biological Preserve. For most of the last two decades, Dr. Field has fostered the emergence of global ecology. His research emphasizes ecological contributions across the range of earth science disciplines. Dr. Field and his colleagues have developed diverse approaches to quantifying large-scale ecosystem processes, using satellites, atmospheric data, models, and census data. They have explored local- and global-scale patterns of climate change impacts, vegetation-climate feedbacks, carbon cycle dynamics, primary production, forest management, and fire. At the ecosystem scale, Dr. Field has, for more than a decade, led major experiments on grassland responses to global change, experiments that integrate approaches from molecular biology to remote sensing. His activities in building the culture of global ecology include service on many national and international committees, including committees of the National Research Council, the International Geosphere-Biosphere Programme, and the Earth System Science Partnership. Dr. Field was a coordinating lead author for the fourth assessment report of the Intergovernmental Panel on Climate Change. He is a fellow of the Ecological Society of America's Aldo Leopold Leadership Program and a member of the U.S. National Academy of Sciences. He has served on the editorial boards of *Ecology*, *Ecological Applications*, *Ecosystems*, *Global Change Biology*, and *Proceedings of the National Academy of Sciences (PNAS).* Dr. Field received his Ph.D. from Stanford in 1981 and has been at the Carnegie Institution since 1984. His recent priorities include high-performance "green" laboratories, integrity in the use of science by governments, local efforts to reduce carbon emissions, ecological impacts of biofuels, and the future of scientific publishing.

Jeffrey I. Gordon, M.D. (NAS/IOM), is the Dr. Robert J. Glaser Distinguished University Professor and Director of the Center for Genome Sciences at Washington University School of Medicine. He received his A.B. in biology from Oberlin College and his M.D. from the University of Chicago. Dr. Gordon joined the faculty of Washington University in 1981, after completing his clinical training in internal medicine and gastroenterology. He has remained at Washington University for his entire professional career. From 1991 to 2004, he was head of the Department of Molecular Biology and Pharmacology. In 2004 he resigned as department head to become the first director of the newly founded Center for Genome Sciences. This new center represents an interdepartmental, interdisciplinary, and multigenerational intentional community of faculty, postdocs, and students who are geneticists, population biologists and biostatisticians, computational biologists and computer scientists, systems biologists and engineers, and microbiologists and ecologists. The focus of the center is on comparative genomics and biodiversity, plus systems biology (an emerging area that seeks to describe how complex networks of interacting genes, proteins, and metabolites function to maintain normal cells and how these networks adapt to perturbations, including those brought about by various disease states). Dr. Gordon's lab studies the genomic and metabolic foundations of mutually beneficial host-microbial relationships in the human gut with an emphasis on the interrelationships between the gut microbiome, diet, and nutritional status. He has published more than 400 scientific papers and is named as inventor or co-inventor on 23 U.S. patents. He has received a number of honors in recognition of his scientific contributions, including election to the National Academy of Sciences, the Institute of Medicine, and the American Academy of Arts and Sciences.

Pedro A. Sanchez, Ph.D., is director of tropical agriculture and senior research scholar at the Earth Institute of Columbia University in New York City. He serves as co-chair of the Hunger Task Force of the Millennium Project, an advisory body to the United Nations. Sanchez served as director general of the World Agroforestry Center (ICRAF) headquartered in Nairobi, Kenya, from 1991 to 2001. He is also professor emeritus of soil science and forestry at North Carolina State University and was a visiting professor at the University of California, Berkeley. He was named a MacArthur Foundation fellow in 2003 and received the World Food Prize in 2002. His professional career has been dedicated to improving the management of tropical soils through integrated natural resource management approaches to achieve food security and reduce rural poverty while protecting and enhancing the environment. Sanchez is author of *Properties and Management of Soils of the Tropics* (John Wiley and Sons 1976; rated among the top 10 best-selling books in soil science worldwide), and author of more than 200 scientific publications. He is a fellow of the American Society of Agronomy and the Soil Science Society of America. He has received decorations from the governments of Colombia and Peru and was awarded the International Soil Science Award and the International Service in Agronomy Award. In 2001, the Catholic University of Leuven, Belgium, awarded him a doctor honoris causa degree for his work on tropical soils in Africa and he was anointed as elder by the Luo community of Western Kenya, in recognition for his assistance in eliminating hunger from many villages in the region. A native of Cuba, he received his Ph.D. degree from Cornell University.

Christopher R. Somerville, Ph.D. (NAS), is the director of the Energy BioSciences Institute in Berkeley, California. He oversees all activities at the institute, including research, communication, education, and outreach. He also chairs the institute's Executive Committee. Dr. Somerville is a professor in the Department of Plant and Microbial Biology at the University of California, Berkeley, and a visiting scientist at the Lawrence

Berkeley National Laboratory. His research focuses on the characterization of proteins implicated in plant cell-wall synthesis and modification. He has published more than 200 scientific papers in plant and microbial genetics, genomics, biochemistry, and biotechnology. Dr. Somerville has served on the scientific advisory boards of many corporations, academic institutions, and private foundations in Europe and North America. He is a member of the National Academy of Sciences, the Royal Society of London, and the Royal Society of Canada.

Appendix B

Workshop Background

WORKSHOP STATEMENT OF TASK

The 2009 report *A New Biology for the 21st Century* offered a vision that enables powerful advances in the life sciences to provide solutions to major global problems. As part of the follow-on activities stemming from the report, the Board on Life Sciences plans to organize a series of workshops to provide concrete examples of how the life sciences could contribute to addressing these grand challenges.

For the first of these, an ad hoc committee will organize a public workshop on meeting the intertwined challenges of increasing food and energy resources in a context of environmental stress, in which participants will:

- Identify a small number of concrete problems for the New Biology to solve—problems that are important and urgent (and therefore inspirational), intractable with current knowledge and technology, but perhaps solvable in a decade.
- Identify the knowledge gaps that would need to be filled to achieve those goals.
- Identify conceptual and technological advances essential to achieve those goals.

MEETING AGENDA
IMPLEMENTING THE NEW BIOLOGY: DECADAL CHALLENGES LINKING FOOD, ENERGY, AND THE ENVIRONMENT

Board on Life Sciences, National Research Council

Howard Hughes Medical Institute (HHMI)
4000 Jones Bridge Road • Chevy Chase, MD 20815

WEDNESDAY, JUNE 2, 2010

6:00 p.m. Light buffet dinner for participants who will be arriving early *[Rathskeller Lounge]*

THURSDAY, JUNE 3, 2010

8:00 a.m. Breakfast available until 9:30 a.m. *[Small Dining Room]*

10:00 a.m. **Plenary #1: Welcome to HHMI; Introduction to Workshop** *[Small Auditorium]*
Chair: Robert Tjian, *President, Howard Hughes Medical Institute; Professor of Biochemistry and Molecular Biology, University of California, Berkeley*
- Keith Yamamoto, *Chair, Board on Life Sciences, National Research Council; Professor of Cellular and Molecular Pharmacology and Executive Vice Dean, School of Medicine, University of California, San Francisco*
- Roger Beachy, *Director, National Institute of Food and Agriculture, U.S. Department of Agriculture*
- Steven Koonin, *Under Secretary for Science, U.S. Department of Energy*

10:30 a.m. **"Elevator" Talks** *[Small Auditorium]*
- Each participant will have three minutes to present his or her transformative idea

12:00 p.m. **Breakout #1** (in assigned small groups) during **lunch** *[See breakout group assignment and locations]*
- Discuss elevator talks

- Choose top three Big Ideas from elevator talks or develop new transformative ideas by combining, refining, and building on elevator talks, or de novo
- Place each idea on the New Biology quadrant
- For each idea, explain the following:
  - Degree of risk or likelihood of success
  - Why it requires cross-agency effort and why it won't happen any other way
  - Why it's important: impact, if successful, on agriculture, energy, environment, health

2:15 p.m. Break

2:30 p.m. **Plenary #2: Prioritization** *[Small Auditorium]*

- Breakout group progress reports
- Plenary Discussion: *prioritize*
  - Refine and perhaps begin to cluster ideas
  - Initial brainstorming on cross-cutting knowledge areas and technologies or shared resources that might contribute to multiple "decadal challenges"

4:00 p.m. **Breakout #2** *[See breakout group assignments and locations]*

- Begin to identify the "decadal-level" research problems and questions that investigators could address in order to achieve them
- Questions include the following:
  - What is needed in terms of basic knowledge, new technologies, and infrastructure?
  - What other fields need to be involved?
  - What educational programs are needed to produce the right kinds of researchers?
- Consideration of timing, sequence, and interactions among ideas

5:30 p.m. Break

6:15 p.m. **Dinner** (in mixed groups) *[Small Dining Room]*

- Representative from each group should brief dinner companions on the day's discussions; scribes take notes

8:00 p.m. Continued interactions and discussion *[Rathskeller Lounge]*
Steering committee meeting with rapporteurs

FRIDAY, JUNE 4, 2010

7:30 a.m. Breakfast available until 8:30 a.m. *[Small Dining Room]*

8:30 a.m. **Plenary #3: Development of Decadal-Level Agenda** *[Small Auditorium]*
- Reports of dinner discussions
- Development of master chart
- Organization of Breakout #3

10:00 a.m. Break

10:15 a.m. **Breakout #3** (as determined in plenary #3) *[Rooms N-140, N-238, S-221]*

11:30 a.m. **Plenary #4: Small-Group Breakout Reports** *[Small Auditorium]*

12:30 p.m. **Lunch** (Steering committee and rapporteurs meet again) *[Small Dining Room]*

1:30 p.m. **Breakout #4: Gap Filling** (as determined over lunch) *[Rooms N-140, N-238, S-221]*
- Goal is to capture all ideas: the resulting workshop report will include *only* ideas discussed at the workshop

2:30 p.m. **Final Plenary** *[Small Auditorium]*
- Identify immediate priorities: top five actions that need to happen in the next year
- Getting the message out: brainstorming on how participants can continue to be involved in the New Biology effort

3:30 p.m. **Adjourn**

Direct and in-kind support for the workshop has been provided by the U.S. Department of Energy, U.S. Department of Agriculture, Gordon and Betty Moore Foundation, and Howard Hughes Medical Institute.

A New Biology for the 21st Century was supported by the National Institutes of Health, the National Science Foundation, and the U.S. Department of Energy.

LIST OF PARTICIPANTS IMPLEMENTING THE NEW BIOLOGY: DECADAL CHALLENGES LINKING FOOD, ENERGY AND THE ENVIRONMENT

Board on Life Sciences, National Research Council

June 3-4, 2010 • Howard Hughes Medical Institute, Chevy Chase, Maryland

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