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The US Department of Energy Great Lakes Bioenergy Research Center: Midwestern Biomass as a Resource for Renewable Fuels

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Abstract The Great Lakes Bioenergy Research Center is one of three Bioenergy Research Centers establish by the US Department of Energy and the only one based at an academic institution. The Center's mission is to perform basic and applied science to enable economically and environmentally sustainable production of liquid fuels derived from biomass. The research is focused on converting plant biomass into soluble sugars and the sugars into fuels. A large group focused on sustainability informs and guides the applied research to ensure that new technology will provide the required environmental benefits.

Keywords Bioenergy · Biofuels · Sustainability

Introduction

Plant biomass is one of the earth's primary means for capturing and storing solar energy, and this energy has traditionally been released by humans through direct combustion of wood. But plant biomass is mainly composed of polymeric sugars (cellulose and hemicellulose) that can be depolymerized and converted, through biological or chemical means, to liquid fuels and related chemicals. A 2006 study by the US Department of Energy suggests that over a billion tons of plant biomass is potentially available for conversion to liquid fuel, enough to replace 30% of annual US gasoline consumption [14]. However, these processes are neither easy nor inexpensive, so exploiting this potential requires new technology to grow, harvest, deconstruct, and convert plant biomass to fuels. It will also require new agricultural and economic models and potentially new distribution systems. Enabling this nascent biofuels landscape is the objective of the DOE Bioenergy Research Centers, which were funded in 2007 by the US Department of Energy's Office of Science.

The Great Lakes Bioenergy Research Center is one of three DOE Bioenergy Research Centers (BRCs) and the only one based at an academic institution (the other two are based at DOE National Laboratories [17]). All three centers share a common directive from DOE: to perform mission-relevant basic science that enables development of liquid fuels derived from cellulosic biomass. Great Lakes Bioenergy is led by the University of Wisconsin–Madison, with Michigan State University as the major partner. Additional scientific partners include DOE National Laboratories (Pacific Northwest and Oak Ridge National Labs), Iowa State University, Illinois State University, and the biotechnology company Lucigen. Much of this research is driven by genomics technology, and a partnership with the DOE Joint Genome Institute is a critical piece of this strategy. Great Lakes Bioenergy has a Midwestern focus, with research and modeling built around crops (switchgrass, native prairie, and corn stover) that are likely to be grown in the Great Lakes region. However, lessons from

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these models are expected to be applicable to biomass-based systems worldwide.

Great Lakes Bioenergy pursues a highly integrated, systems-based, cross-disciplinary research program. During its first 2 years, the Center has grown to include nearly 350 scientists and support personnel with expertise ranging from soil science to microbiology to economics to engineering. As the only academically based BRC, the Center leverages the inherent benefits of individual investigator creativity while providing the high-throughput core facilities needed to make transformational discoveries. The Center includes four Research Thrust Areas (see below), led by university faculty, that are focused on modifying plant biomass, deconstructing plant biomass, converting soluble sugars into fuels, and developing sustainable production systems. It also contains Scientific Support Areas, focused on Enabling Technologies (transcript profiling, proteomics, metabolomics, etc.), Informatics and Information Technology, Education and Outreach, and Business and Science Operations teams that support the entire Center. A Scientific Advisory Board that includes leaders from academics, industry, venture capitol, and the other BRCs provides advice regarding the components and integration of its research portfolio.

Missions of the Research Thrusts and Supporting Areas

Thrust 1: Modifying Plant Biomass Among the bottlenecks in using current plants for bioenergy production are the difficulty of degrading the major constituents of cell walls (cellulose, hemicelluloses, and lignin) and the inability of many plants to store carbon in energy-rich hydrocarbon forms. The Center has two major long-term goals for improving plant biomass: to increase the yields of easily degraded polysaccharides or easily fermentable sugars within plant cell walls and to increase the yields of energy-rich hydrocarbons (oils) in harvested tissues [3]. To achieve these long-term goals, the Center strives to decipher, model, and redirect plant carbon into pathways that increase their value to the bioenergy marketplace. It combines genetic, biochemical, and bioinformatic approaches with high-throughput platforms to analyze changes in cell wall structure and identify underlying genetic changes [4, 6, 12, 15]. One short-term goal is to generate fundamental understanding of relevant pathways in model plants, including a systems-level understanding of the relevant metabolic and regulatory networks that control plant cell wall and hydrocarbon synthesis. Once this blueprint is available, the Center will use this knowledge to identify or create new biomass feedstocks for biofuels production.

Thrust 2: Deconstructing Plant Biomass Processing of plant biomass to sugars is another bottleneck in the production of cellulosic ethanol or other bioenergy products. New physical and biological treatments are needed for processing the feedstocks (e.g., maize stover, switchgrass, or poplar) envisioned for the bioenergy pipeline. Great Lakes Bioenergy is developing novel combinations of physical and enzyme treatments that are tailored to biomass composition. The Center's primary physicochemical pretreatments for biomass include Ammonia Fiber Expansion (AFEX; [1]) and other pretreatments that depend on elevated pH. Researchers are identifying and quantifying small molecules generated by different pretreatment methods and examining how these molecules impact biofuel yield. The Center also has a bioprospecting program to query relevant environments for novel biomass processing activities, with particular focus on microbes associated with biomass-utilizing insects such as leaf-cutter ants [10]. The Center is exploring optimal combinations of enzymes, chemicals, and physical processing, and doing so in the context of economic modeling of production costs.

Thrust 3: Converting Soluble Sugars into Fuels These projects aim to overcome fundamental problems with producing fuels and other chemical intermediates using sugars derived from biomass. These bottlenecks include cost-effective production of lignocellulolytic enzymes by consolidated bioprocessing microbes, microbial tolerance of toxins in biomass feedstocks and of biofuels in fermentations, efficient transport and metabolic conversion of diverse mono- and oligosaccharides, direction of carbon skeletons and reducing power into strategic precursors and fuels, and cost-effective chemical catalysts for biofuel production. The biological projects use an iterative program of strain selection and metabolic engineering to improve the ability of microbes to convert cellulosic biomass into ethanol or other molecules. These processes lean heavily on DNA sequencing, transcriptomics, metabolomics, proteomics, and other high-throughput technologies for analysis of cellular status [15]. In addition, the Center funds work on discovery chemistry designed for direct conversion of mono- or polysaccharides, including the complex mixtures derived from biomass, to other useful chemical intermediates that are currently derived from fossil fuels [2, 7].

Thrust 4: Sustainability For a bioenergy economy to positively impact the US energy sector, one must create new agricultural, industrial, and behavioral systems [13]. A long-term goal of Great Lakes Bioenergy is to develop and deploy biofuel cropping systems that are both profitable and environmentally sustainable. To achieve this goal, the Center analyzes the attributes of sustainable biofuel production systems across multiple scales to obtain the knowledge needed to design and deploy scalable systems that meet economic and environmental goals [8, 9, 11]. The Center has also initiated programs to identify the social or

financial incentives needed to adopt bioenergy practices of high economic and environmental benefit [5].

Supporting Research Areas The Center's success hinges on application of enabling biological, physical, and chemical systems, and computational approaches to the four discovery thrusts [14, 15]. The Enabling Technologies group leverages high-throughput transcript, protein, and metabolite measurements to quantify chemical, gene expression, and genome-level changes in biomass plants or microbes. In close collaboration with the IIT team (see below), information is used to generate predictive models that guide the biochemical, genetic, and transgenic approaches employed to develop biomass plants and microbes, design improved catalysts, or direct the flux of carbon and reducing power into bioenergy products. The Informatics and Information Technology (IIT) group supports center-wide activities that require computational and/or data-management infrastructure. It develops systems for managing data produced by research and management teams and works closely with center members to support individual science projects and ensure that computational needs are integrated and aligned across the center. In addition, all three of the DOE Bioenergy Research Centers are beginning to cooperatively develop a bioenergy knowledgebase that will support systems biology for the scientific community and permit sharing of data among the BRCs [16]. The Education and Outreach group works in the tradition of Land Grant institutions to enhance the broad understanding of contemporary issues of bioenergy for a diverse array of audiences including students and teachers involved in formal education (K-16), technical colleges, agricultural and industrial sectors, and the general public. Educational programs are developed in concert with the Center's scientists to keep the programs relevant and up-to-date. The goal is to create a scientifically literate citizenry who consider bioenergy issues using critical thinking, quantitative reasoning and systems-based logic.

Conclusions

Innovation occurs most readily where different fields of research overlap, creating new syntheses of ideas and technology. The Great Lakes Bioenergy Research Center is committed to increasing the quality, quantity, and durability of these scientific overlaps as a means to rapidly advance biofuels research. This requires focus on both the details of the science and the sociology of the scientific endeavor. By funding Bioenergy Research Centers, rather than a series of individual research grants, the DOE has catalyzed both the science and the social networks needed to make transformational changes in biofuels research.

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