Energize Missouri: Algae-Based Renewable Energy Study

Task B
Missouri's Algal Biofuels Research, Resource and Industrial Assets

Final Report

For
Missouri Technology Corporation

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For
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Attn: Jason Hall

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Preface

This report was prepared for the Missouri Technology Corporation under a subgrant award to MRIGlobal and entitled "Energize Missouri: Algae-Based Renewable Energy Study," signed by Mr. Jason Hall, and dated February 28, 2011. Work was initiated in accordance with a work plan submitted and approved on March 11, 2011. The project team includes members from MRIGlobal, Washington University in Saint Louis, and the University of Missouri, Columbia.

The objective of the grant is to produce a study to help define the development and commercialization of algae as a fuel source that would be a valuable adjunct to the state energy plan. The study would emphasize the potential benefits to the state economy that a commercial algae industry could bring, opportunities for Missouri to become a leader in such an industry, and the policy steps and collaborations that the state could initiate to strengthen Missouri's leadership in this area. The study is divided into seven tasks plus a final report. This report is the results of Task B which sought to identify and document Missouri's algae-based bio-fuel research and industrial assets.

This Task B study was authored by Jay Turner of Washington University in St. Louis (WUSTL) as Principal Investigator, and co-authored by John Murphy (WUSTL). The authors wish to acknowledge contributions by Bill Babiuch, Stanley Bull, Gregory Karr, and Thomas Grant (MRIGlobal). We also gratefully acknowledge conversations with Richard Sayre (Donald Danforth Plant Science Center), Tom Verry and Shelby Neal (National Biodiesel Board), and Richard Axelbaum, Robert Blankenship, Raymond Ehrhard, Mark Henson, and Himadri Pakrasi (WUSTL).

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Section 1. Introduction

The Task A report provided an overview of the algal biofuels enterprise within the context of current and anticipated energy needs. Section 5 of that report briefly summarized Missouri's assets for the algal biofuels industry. This Task B report elaborates on these assets that will be placed in a national and global context in Task C, and critically assessed in Task D. For reasons described in the Task A report, the focus is on biodiesel production.

Biodiesel is diesel fuel made from virgin agricultural products such as vegetable oils and rendered animal fats (tallow) or recycled agricultural oils such as used cooking oils (yellow grease). It is a "drop-in" replacement for the petroleum diesel segment of transportation fuels market. Soy oil currently is the principal feedstock for biodiesel, although other feedstocks exist, and processors are trying to expand the types of feedstocks used. The reliance on soy oil for biodiesel and corn for ethanol has led to the Midwest becoming the primary source of bio-based transportation fuels. Transportation of the feedstocks to the processor is a key cost element, so the processors have located near the feedstock suppliers. Thus, for a variety of economic and climate reasons, Missouri has grown into one of the principal centers for the production of biodiesel.

The biodiesel industry in Missouri is strong with nine plants located within the state. However, not all of the plants are in currently production for a variety of economic, regulatory, and technical reasons. The most successful facilities tend to have expertise provided by companies with established track records in the industry, such as Cargill and ADM. Missouri is also home to the National Biodiesel Board (NBB), a national trade and advocacy group headquartered in Jefferson City that represents the biodiesel industry. There is clearly substantial biodiesel expertise resident in the State of Missouri.

While there are numerous similarities between the current state of the biodiesel industry, which relies on established agricultural products like soy oil, and a future biodiesel industry using algae, there are also important differences. Using algae for biofuels presents substantial economic challenges as both agricultural products and transportation fuels are commodities with global markets. There are numerous, interrelated factors that can impact the industry's economics. As discussed in Task A, the cost-competitive production of algae, and conversion to biodiesel, will require a wide range of skills in biology, engineering, and industrial processing.

The wide range of factors influencing the viability of an algal biofuel industry demands a wide range of expertise. Several organizations within the State of Missouri are currently addressing various aspects of this industry. This task focuses on current activities within Missouri. Given that algae-based biofuels should still be considered one of "tomorrow's" fuels, much of this activity centers on research and development. However, it is becoming clear that industrial expertise is needed. Algae cultivation also has certain resource requirements that influence geographic locations favorable for siting. Thus, this assessment is divided into three distinct components (1) research and development activities, (2) industrial assets, and (3) factors that affect the opportunity for large-scale cultivation of algae in the State of Missouri.

Section 2.
Research and Development Activities

A host of Missouri-based institutions are active in assessing and addressing research needs in the algal biofuels field. The list of these institutions and their principal focus areas is given in **Table 1**. A brief summary of the activities of each institution follows.

Donald Danforth Plant Science Center (DDPSC). DDPSC is conducting extensive basic research into the biology and genetic engineering of various bio-oils from algae, soy and other plants. Further, the Center is home to several regional, national and international collaborations which conduct basic research into algae biology and develop techniques to assist in the scale-up of algae cultivation, harvesting and processing. These efforts include:

- Enterprise Rent-A-Car Institute for Renewable Fuels, recipient of a $15 million USDOE grant to develop an Energy Frontier Research Center at the Institute.
- Center for Advanced Biofuel Systems, which focuses on improving current biofuel production efficiency and decreasing reliance on food crops through engineering of metabolic networks in algae species.
- National Alliance for Advanced Biofuels and Bioproducts (NAABB). DDPSC is the home of this international consortium of academic, industrial and national laboratories which is addressing algal biology, cultivation, harvesting and extraction, fuel conversion, development of co-products, and sustainability analysis. The USDOE provided initial funding of $44 million for the alliance and additional matching funds has made this effort significantly larger.

Lincoln University. Lincoln University has partnered with Missouri University of Science and Technology, and Associated Electric Cooperative Inc. (AECI), in a field evaluation of using flue gas from a coal-fired power plant to grow algae. The study is currently underway at Central Electric Cooperative's 70 MW coal-fired Chamois power plant that is located in Osage County on the Missouri River. The study is unique in two ways: it focuses on wild strains of algae native to Missouri, and it uses flue gas from an actual power plant. Both aspects are extremely important in making algal-based biofuels more economical in the near term, and in evaluating the potential benefits to minimizing greenhouse gas emissions.

For this project the algae are currently grown on a batch basis in 1,000 gallon tanks. Researchers hope to build raceways adjacent to the tanks to assess scale-up issues associated with the most promising strains. In addition, the raceways will enable researchers to further quantify greenhouse gas emission reductions by using the power plant's flue gas. To date the study has obtained approximately $200,000 in funding which includes in-kind contributions from the electric utility.

Missouri University of Science & Technology (Missouri S&T). Researchers at Missouri S&T are partnering with Lincoln University in the study described above. Missouri S&T researchers are focused on algal chemistry and scale up issues while the Lincoln University team is focused on algal biology and is the public "voice" for the project.

Table 1. Research and Development Activity in Algal-based Biofuels in the State of Missouri.

Institution	Focus	Contact
Danforth Plant Science Center [St. Louis]	National Alliance for Advanced Biofuels and Bioproducts; research and development of genetically optimized algae strains	Richard Sayre, PhD
Lincoln University [Jefferson City]	Field trials of algae cultivation using flue gas from coal-fired power plant	Keesoo Lee, PhD
Missouri University of Science & Technology [Rolla]	Field trials of algae cultivation/harvesting using flue gas from coal-fired power plant	Paul Namm, PhD
MRIGlobal [Kansas City]	Center for Integrated Algal Research—photobioreactor engineering; diversification of output from algal farms; nutrient recycling from WWTPs	Thomas Grant, PhD, PE
University of Missouri-Columbia [Columbia]	Algal raceway integration with tilapia; Rural Policy Research Institute—Agricultural Economics	Dave Brune, PhD Tom Johnson, PhD
Washington University [St. Louis]	I-CARES—algae research including but not limited to genetic modification and techno-economic lifecycle analysis for algal biodiesel production; Consortium for Clean Coal Utilization -photobioreactors using fossil fuel combustion flue gas Photosynthetic Antennae Research Center (PARC)—basic research into solar energy collection by photosynthetic organisms such as algae	Hamadri Pakrasi, PhD Richard Axelbaum, PhD Robert Blankenship, PhD
National Biodiesel Board [Jefferson City]	Coordinating industry association for R&D, regulatory aspects, and marketing of biodiesel in the U.S.	Tom Verry

MRI Global. MRIGlobal established their Center for Integrated Algal Research in 2007. The Center is home to all of MRIGlobal's activities in the algal biofuels research area. State-of-art laboratories located in Florida, Maryland, and Missouri provide clients with customized research and development applications. MRIGlobal's algae-related laboratory resources include:

- Enclosed hybrid photobioreactor systems (Missouri)
- Continuous flow, closed loop photobioreactor
- Open bioreactor systems (pond and raceway cultivation systems) (Florida)
- Dedicated algal laboratories
- Bench and pilot scale processing equipment (harvesting, oil extraction, conversion)

Besides the development of physical resources, the new Center can leverage existing expertise in biotechnology, chemistry, systems engineering and bioinformatics. The Center operates within the company's Energy Programs section, which is headed by Dr. Stan Bull, formerly an associate director at the National Renewable Energy Laboratory who has worked in the renewable energy field—including biofuels - for over 30 years.

University of Missouri-Columbia (UM). Research into algal-based biofuels at the University of Missouri resides principally in the University's College of Agriculture, Food and Natural Resources, with additional expertise in the College of Engineering. For instance, one researcher is planning to construct a raceway pond at the University's Bradford Farm to replicate research conducted in Southern California. The research will focus on harvesting of algae using higher ordered species, such as tilapia or brine shrimp, rather than direct harvesting. The shrimp are harvested to extract the oil while the tilapias reduce zooplankton and minimize algal waste.

Additionally, UM is home to the Rural Policy Research Institute which provides analysis and information on the opportunities, challenges, and needs, and faced by rural America. The Institute has developed a variety of tools to evaluate the impacts of biofuels on agricultural economics. The most prominent of these is the Biopower Tool Kit which provides pre-investment feasibility analyses of biopower projects. The tool is designed to assist in determining the soundness of the economic investment along with estimates of jobs and economic potential. Inputs can include solid wastes such as crop residues and wood waste, along with gaseous biofuels such as landfill or digester gas and coal gasification.

Washington University in St. Louis. Washington University is deeply engaged in algal biofuels research through a variety of consortiums and collaborative efforts. Given the complex and multidisciplinary nature of energy issues, in 2007 the University formed the International Center for Advanced Renewable Energy and Sustainability (I-CARES). I-CARES nurtures collaboration across the University and around the world in identifying and addressing the global energy needs. The University is investing over $50 million in the Center through the construction of a new building, the funding of five new endowed professorships, and the funding of various research projects over the first five years.

To date, I-CARES has explored a variety of issues associated with algal biofuels, including the use of specific algae strains, and the potential for direct co-firing of algal biomass in a coal-fired boiler. One outgrowth of I-CARES is the Consortium for Clean Coal Utilization, which is a partnership between Washington University, Peabody Coal, Arch Coal, Ameren Energy, the Electric Power Research Institute, and partner universities representing 19 countries. The Consortium constructed a 1 MW research boiler on campus to assess various combustion and emission control technologies, along with fuel mixes and materials development. Flue gas from the boiler is routed through five research photobioreactors for use in the cultivation of algae.

Washington University is also home to the Photosynthetic Antennae Research Center (PARC), one of the USDOE Energy Frontier Research Centers. PARC conducts basic research into the mechanisms of light capture and utilization by organisms, and a portion of the Center's research portfolio is directly relevant to algae.

National Biodiesel Board (NBB). NBB was initially formed by soybean farmers looking to diversify uses for their product. Shortly after its creation in the early 1990's, the NBB chose to expand its mission to include suppliers with all types of feedstocks. Thus, the NBB embraces and advocates the development of algae for biofuels. From its headquarters in Jefferson City, the NBB now sponsors research and serves as a policy advocate at both the state and national level for biodiesel. NBB is active in funding a variety of research efforts towards improving biodiesel development using all feedstocks, including algae. In addition, the NBB has significant experience in policy development at both the state and national levels. Regulatory policy through certain channels like RFS2 and California's greenhouse gas emission reductions program could have an enormous impact on the economic viability of biofuels. NBB is an excellent source of information on national activities in the field and the most effective ways to move the industry forward through regulatory programs.

In summary, Missouri has substantial R&D assets in biofuels including algal feedstocks. This preliminary inventory of R&D assets is not comprehensive—R&D tends to be "siloed," and thus the potential for algae to play a role in the nation's future energy mix could attract talent from allied disciplines. However, based on this assessment alone it is clear that Missouri has extensive strengths in the R&D of algae for biofuels. In fact, Biofuels Digest readers named St. Louis the "King of Algae" in 2009, beating out Silicon Valley, Seattle and San Diego. Given the ongoing importance of agriculture to the state's economy, there is significant research infrastructure in place in the biological, engineering and economic arenas needed to move the algae biofuels industry forward.

Section 3.
Industrial Assets

A second area of interest in cataloging Missouri's assets is an assessment of the know-how and skills needed to move from pilot-scale facilities to commercial-scale. Currently, there is no commercial scale algae-to-biofuels plant in the U.S., although a 300-acre biorefinery by Sapphire Energy is under construction in southern New Mexico. There continue to be considerable questions about the potential for and limits to full-scale harvesting and oil extraction, along with possible uses for the biomass remaining after extraction. Some of these issues are research questions, but others are the purview of engineers and will likely best be addressed by companies and organizations already involved in these issues.

Given the historical importance of Missouri's agricultural industry, there is an impressive list of industrial assets which could play a role in a future algal biofuels industry. A summary of these assets, which is by no means comprehensive, is presented in **Table 2** and discussed below.

Biorefineries. Missouri is home to nine biodiesel refineries scattered throughout the state. It has been challenging to document the precise status of some of these biodiesel refineries and this summary reflects our current understanding based on various sources on information. At least six of these refineries are currently in production but the problems encountered by the various refineries in the past two years are instructive. The three largest plants are in St. Joseph (owned by AGP, a grain processor), Kansas City (a joint venture between Cargill and a farmers' cooperative), and Mexico (a joint venture between ADM and a farmers' cooperative). In all cases, processing of a commodity crop to a drop-in fuel is the responsibility of a company with substantial expertise in the industrial-scale processing of related feedstocks.

The other three plants in operation are relatively smaller operations located in southeast Missouri and are wholly-owned by a farmers' cooperative. One of the three plants, ME Bioenergy, was idle for three years and only recently was restarted under new management. There is significant concern that these three refineries located in the Missouri Bootheel might face continuing challenges due to their small size. The remaining three plants are under construction but have experienced various delays due to a variety of problems. There is also some question as to whether the current market can justify this number of refineries.

Interestingly, biodiesel processes starting from soy oil are not particularly complicated and the technology is not proprietary. Refiners employ a variety of modifications to the boilerplate design but the process is well established. Unlike the corn ethanol industry, the process is relatively simple and straightforward so there are a number of designers and suppliers to this market and no single dominant player.

Engineering Firms. Full scale cultivation of algae will entail a water-based system very similar to wastewater treatment systems currently used throughout the country. Missouri is home to three engineering firms which have significant expertise in the design and construction of water and wastewater facilities which have skills transferable to the design and construction of

Table 2. Potential Industrial Assets for an Algal Biofuels Industry in the State of Missouri.

Name	Type of Asset	Annual Capacity (million gallons)	Location
Ag Processing (AGP)	Biodiesel Refinery—operating	50	St. Joseph
Paseo Cargill	Biodiesel Refinery—operating	40	Kansas City
Mid American Biofuels, LLC	Biodiesel Refinery—operating	36	Mexico
ME Bioenergy, LLC	Biodiesel Refinery—restarted May 2010	5	Libourn
Global Fuels, LLC	Biodiesel Refinery—operating on chicken fat	3	Dexter
Natural Biodiesel Plant	Biodiesel Refinery (under construction)	5	Hayti
Prairie Pride	Biodiesel Refinery	(33) Not operating	Eve
Terra Bioenergy, LLC	Biodiesel Refinery(under construction)	(20)	St. Joseph
American Energy Producers, Inc	Biodiesel Refinery (under construction)	(50)	Carrollton
Black & Veatch	Engineering Consultant Firm strong in water and wastewater treatment		Kansas City
Burns & McDonnell	Engineering Consultant Firm strong in water and wastewater treatment		Kansas City
Jacobs Engineering	Engineering Consultant with vast construction capabilities		St. Louis
Bunge North America	Exporter and domestic supplier of grain; oilseed processing; biofuels marketing		St. Louis
Monsanto	Agriculture biotech firm—signed deal with Sapphire on algae genetic engineering research		Chesterfield
MFA Oil	Farmer-owned cooperative and distributor of various energy products		Columbia

algae cultivation facilities. Both Black & Veatch Corporation and Burns & McDonnell maintain their core water and wastewater expertise in Kansas City. Black & Veatch is ranked 14th among environmental firms and Burns & McDonnell is 47th. Both firms are significant players in water and wastewater treatment with extensive process and construction management experience in oxidation ditch technology which is very similar to the open raceway pond design used for algae cultivation. Jacobs is a design-build firm with 2010 revenues in excess of $10 billion. They maintain expertise in a variety of relevant fields including water quality and field biology.

Other Firms. There are at least two additional companies with headquarters in Missouri that are particularly relevant to the algal biofuels enterprise. Monsanto is a St. Louis-based life sciences company which is very active in the algae research. Monsanto is currently a partner with Sapphire Energy in their efforts to commercialize algae for biofuels. MFA Oil is headquartered in Columbia and provides marketing and retail expertise for a variety of agricultural products including biodiesel. They are particularly strong at marketing corn-based ethanol for use in gasoline. The company operates a number of retail stores throughout Missouri and Arkansas including 76 Break Time convenience stores and numerous Jiffy Lube franchises in mid-Missouri, along with bulk fuels and propane distribution networks.

Section 4.
Resources for Algal Biofuels Production

Large-scale cultivation of algae in outdoor raceway ponds will require water, sunlight, favorable temperatures, nutrients, and relatively flat land. These factors tend to be available to varying degrees and thus detailed assessments are needed to identify candidate geographic locations for algae cultivation. The key to promoting large-scale cultivation in a cost effective manner is to find the best combination of all of these requirements at the lowest cost. This section provides a brief overview with emphasis on statewide features. A more detailed perspective on the Missouri Bootheel region (**Figure 1**) is presented in the Task D report.

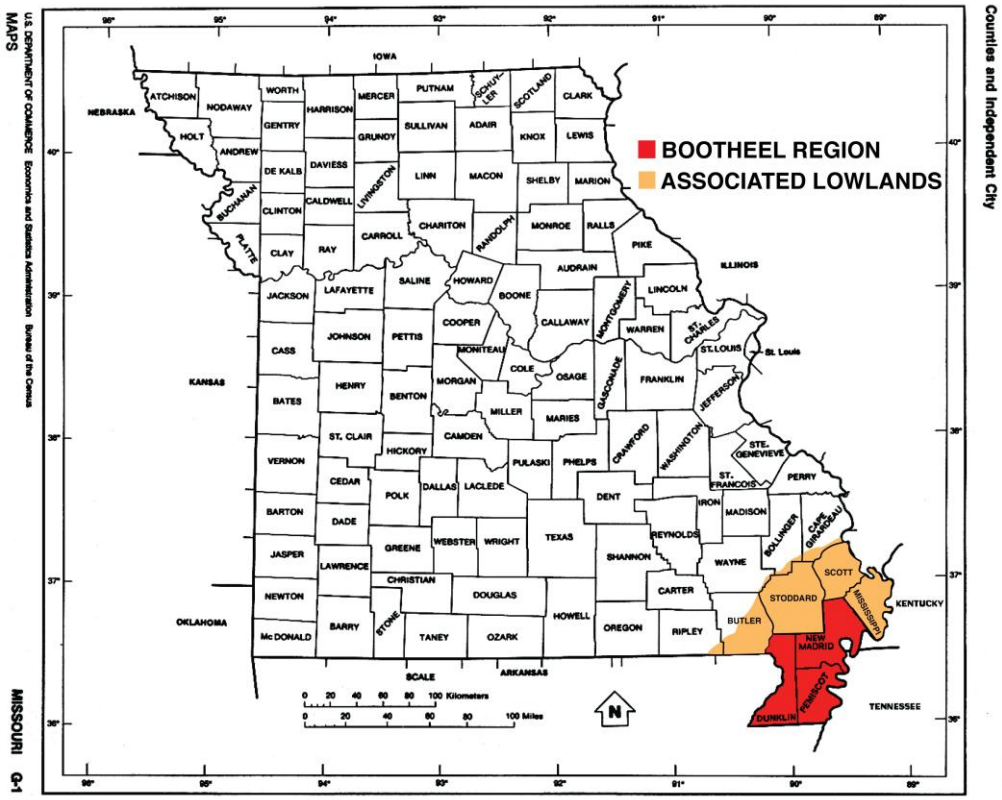

Figure 1. County Map for the State of Missouri Highlighting the Bootheel Region and Associated Lowlands

Climate (Sunlight, Temperature). Missouri winters are relatively cold and this makes the outdoor cultivation of algae a challenge. In fact, the severity of Missouri winters suggests that year-round outdoor algae production is not viable in the absence of pond heating. The Lincoln University research team was able to cultivate algae in January 2010, by using a noncontact heating loop in the tank. The heating source was the power plant's water outfall which has a consistent, year round temperature in excess of 140°F. This approach emphasizes the potentially important role of industrial symbiosis to the algal biofuels enterprise—in this case a waste heat stream from the power plant being used to maintain adequate pond temperature for algae cultivation.

Sunlight is needed to drive the photosynthetic growth of algae. The conventional wisdom that more sunlight is always better may be unfounded, however, because light utilization by algae reaches a saturation point beyond which more intense sunlight does not lead to more rapid growth.

Flat Land. Large-scale scale algae production using open raceway ponds will require large tracts of flat land. For example, the nationwide analysis by Wigmosta *et al.*, (2011) used a screening criterion of no more than one degree of slope to identify 290 hectare plots potentially suitable for algae growth ponds. **Figure 2** shows a land slope map for the State of Missouri. While the southern half of the state is water-rich, it is also quite hilly and rocky with the exception of the Bootheel region and associated lowlands. The northern half of the state is less hilly but in most places fails to meet a one degree slope criterion. In addition to the Bootheel, there are zones with acceptable slope along the Missouri and Mississippi River. These river valleys and the Missouri Bootheel region in general feature broad, flat sections of land, are rich in groundwater and adjacent surface water, and have several nearby utility and industrial facilities that could be sources of CO_2, heat, and nutrients. In many ways, the Missouri and Mississippi River alluvia represent potentially favorable sites for algae cultivation.

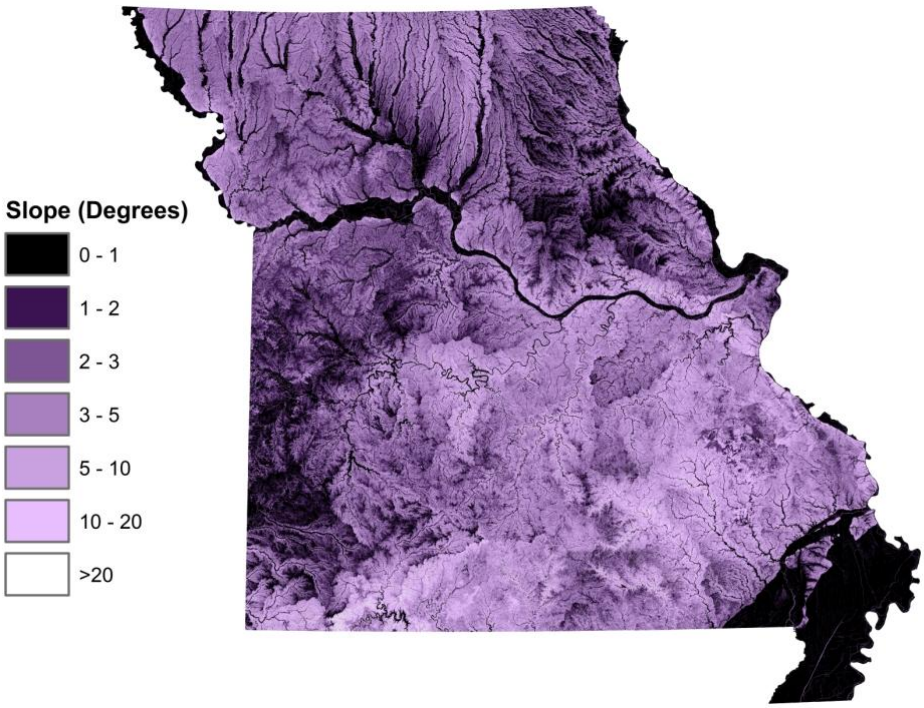

Figure 2. Land Slope in the State of Missouri

Water. With the Missouri River—the continent's longest river—bisecting the state and the Mississippi River running along its eastern border, Missouri in general possesses abundant quantities of water. However, while the southern tier and areas near the Missouri River have access to access plenty of surface water, northern Missouri relies on less available and poorer quality groundwater. Even if the slope criterion of one degree was modestly relaxed such that the northern portion of the state was potentially attractive from the terrain perspective, a lack of adequate water resources might be a major concern. Overall, the Bootheel region again appears to be among the most favorable locations within the state from a water resources perspective.

Carbon Dioxide. Algae growth requires a source of CO_2. While CO_2 is present in air, it is expensive to sparge raceway ponds with the volume of air needed to promote high algae growth rates. Thus, gas streams are desired that are enriched in CO_2 compared to air. **Figure 3** shows the location of point sources in the State of Missouri with large emissions of CO_2. Co-locating algae growth facilities near such could be potentially advantageous to the production economics.

Nutrients. Both phosphorus and nitrogen are needed in large amounts for algae cultivation. One promising source is wastewater treatment plants (**Figure 4**). However, another intriguing possibility is the use of waste from livestock, and in particular from confined animal feeding operations (CAFOs). Currently, waste from CAFOs is a significant operational problem for these farms. Using this material to feed algae could address both energy and environmental needs. Missouri has significant CAFOs in the north central section (hogs), and southwest section (poultry).

The Task A report summarized a recent national-scale assessment that incorporated many of these factors to identify candidate locations for algae cultivation (Wigmosta *et al.* 2011). Unfortunately, Missouri was largely taken out of play in the analysis because a screening criterion was applied that all land currently in cultivation would not be considered. **Figure 5** shows a statewide map of existing land use with an expanded view for southeastern Missouri. Not surprisingly, the relatively flat portions of the state with abundant water are already in cultivation, whereas the regions with relatively hilly terrain and/or less abundant water tend to be pastureland or remain forested. A qualitative assessment based on the above resource needs suggests that the Bootheel region of Missouri might be the most attractive area in the state for algae cultivation if existing cultivation is strategically replaced. This region will be highlighted in the Task D report.

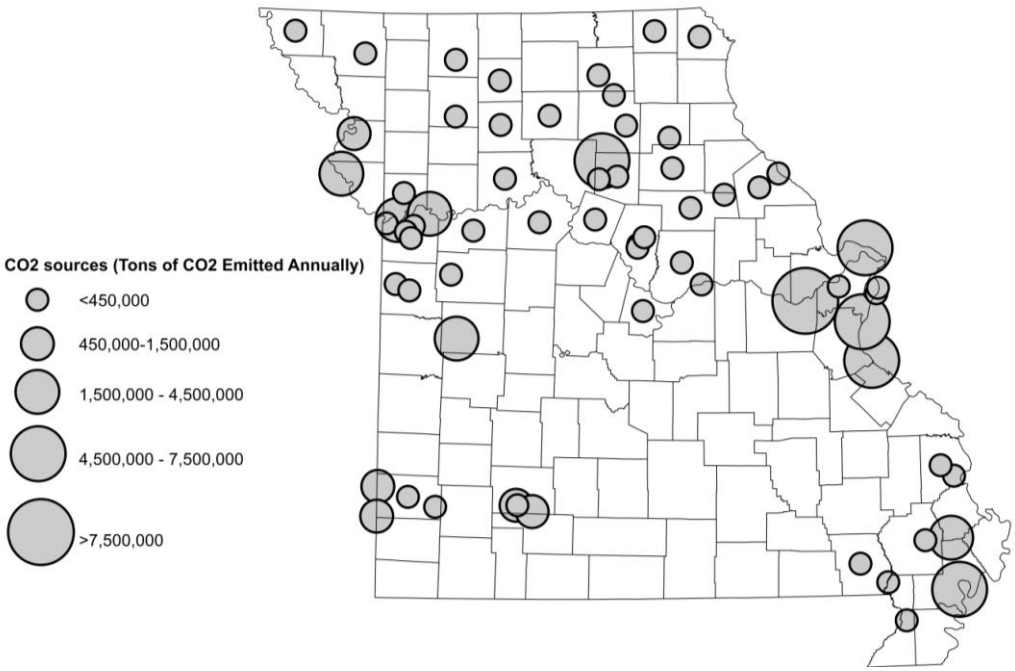

Figure 3. Major CO_2 Emission Point Sources in the State of Missouri

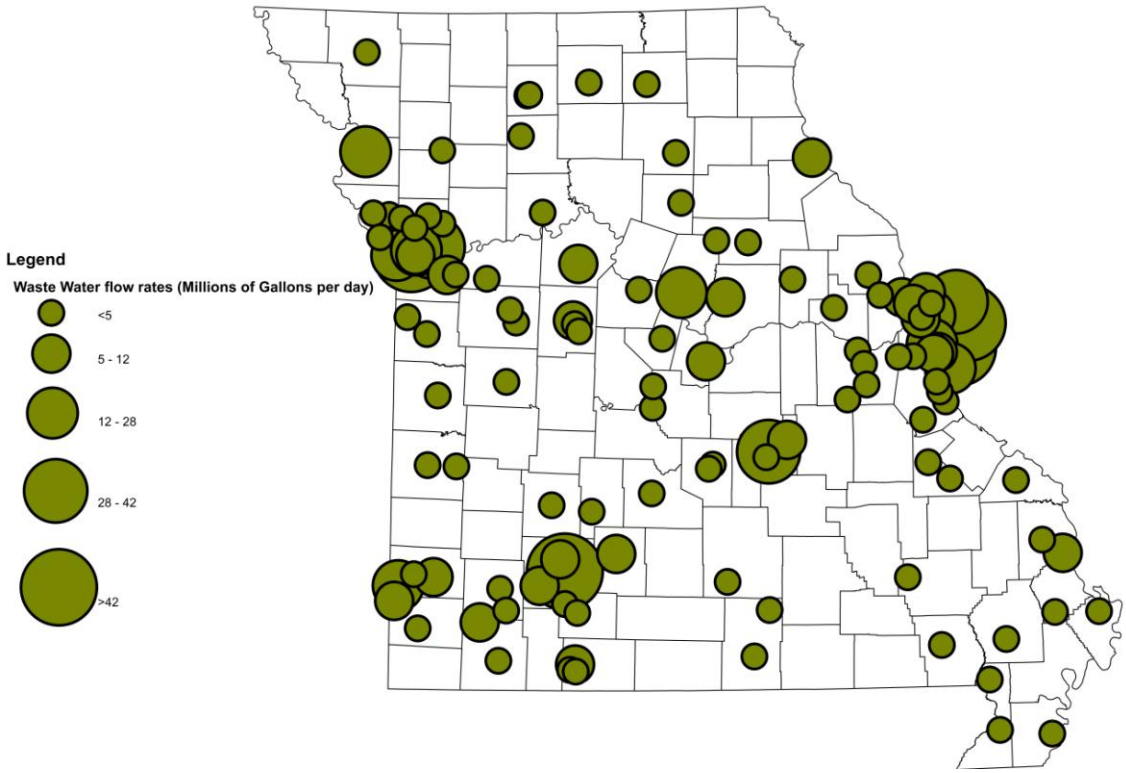

Figure 4. Major Municipal Wastewater Treatment Plants in the State of Missouri

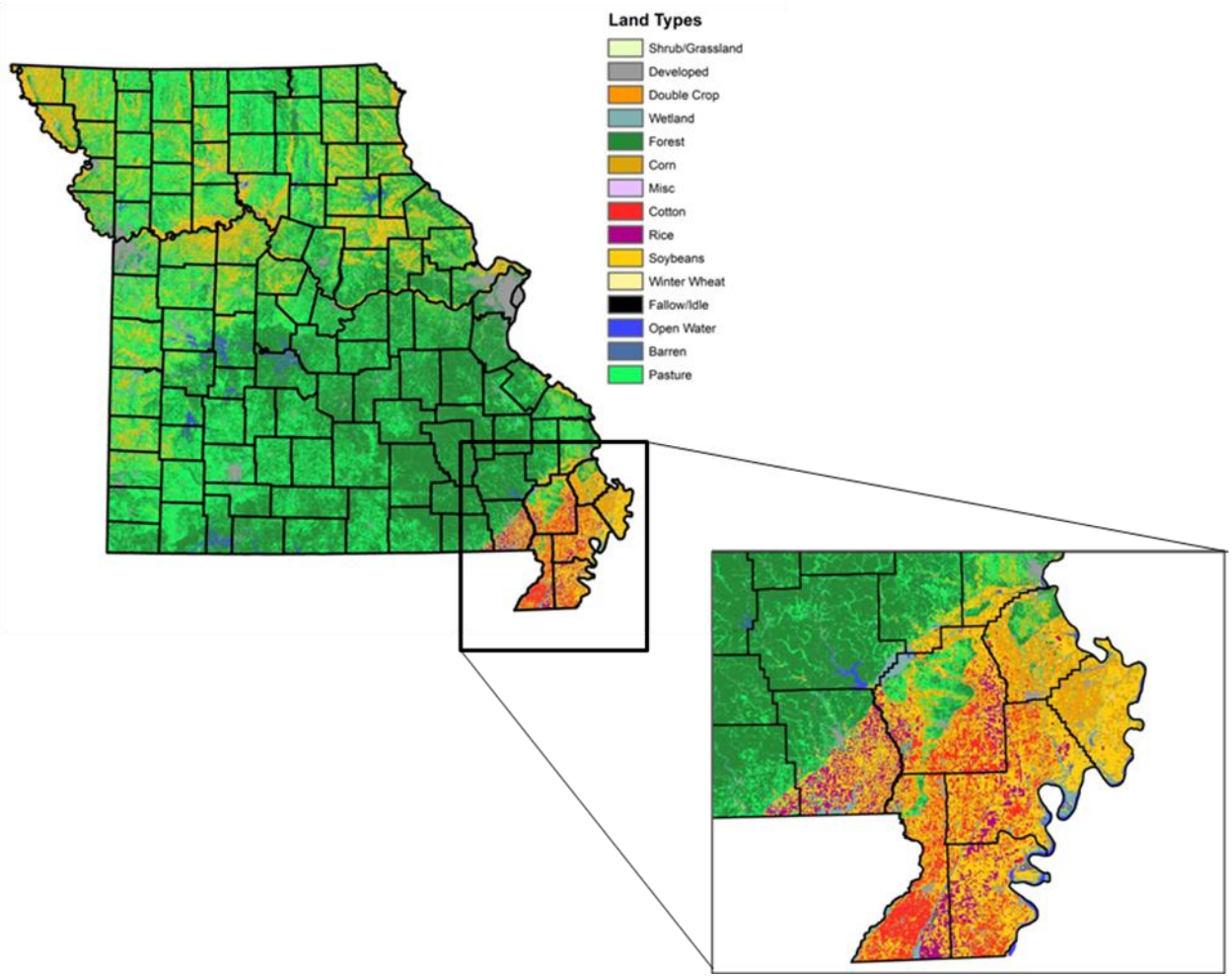

Figure 5. Land use Patterns in the State of Missouri

Section 5.
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