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Bio-Restore Workshop Summary Report

Argonne National Laboratory
September 25–26, 2019

Preface

The mission of the U.S. Department of Energy (DOE) Bioenergy Technologies Office (BETO) is to develop transformative and revolutionary sustainable bioenergy technologies for a prosperous nation. This report summarizes the results of a BETO-sponsored public workshop held at Argonne National Laboratory on September 25–26, 2019.

- This report was funded by and prepared for BETO.
- This report was prepared by BETO and Argonne National Laboratory.

BETO would like to thank those who participated in the workshop.

Disclaimer

The views and opinions of the workshop attendees, as summarized in this document, do not necessarily reflect those of the U.S. government or any agency thereof.

List of Acronyms

ARPA-E	Advanced Research Projects Agency-Energy
BETO	Bioenergy Technologies Office
BioSTAR	Bioenergy Sustainability Tradeoffs Assessment Resource
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
GHG	greenhouse gas
NASA	National Aeronautics and Space Administration
ORNL	Oak Ridge National Laboratory
R&D	research and development
SUNY ESF	State University of New York College of Environmental Science and Forestry
UIUC	University of Illinois at Urbana-Champaign
USDA	U.S. Department of Agriculture
USDA-ARS	U.S. Department of Agriculture Agricultural Research Service
USDA-NRCS	U.S. Department of Agriculture National Resources Conservation Service

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1 Introduction

On September 25–26, 2019, the U.S. Department of Energy (DOE) Energy Efficiency and Renewable Energy Bioenergy Technologies Office (BETO) hosted the “Bio-Restore Workshop” at Argonne National Laboratory.

BETO develops technologies that convert domestic biomass and waste resources into fuels, products, and power to enable affordable energy, economic growth, and innovation in renewable energy and chemicals production. Three subprograms within BETO organized the Bio-Restore Workshop: Feedstock Supply and Logistics, Advanced Algal Systems, and Analysis & Sustainability. The Feedstock Supply and Logistics subprogram develops science-based strategies and technologies to cost-effectively transform renewable carbon sources into high-quality, sustainable, and energy-dense feedstocks for biofuels, bioproducts, and biopower. The Advanced Algal Systems subprogram supports research and development (R&D) to strategically address lowering the costs, improving the quality, and increasing the productivity of algal biomass. The Analysis & Sustainability subprogram develops science-based strategies to understand and enhance the environmental, economic, and social benefits of advanced bioenergy and bioproducts relative to conventional energy systems. All three subprograms seek to develop affordable bioenergy and bioproducts that provide environmental benefits while requiring minimal energy consumption, water use, and nutrient additions.

Current land management practices contribute to environmental problems such as soil erosion, “dead zones” in aquatic systems, and disturbances to habitat and wildlife. A number of studies suggest that terrestrial and algal biomass could reverse and prevent this environmental degradation if produced or harvested with this aim in mind. The “bio-restore” concept refers to leveraging the beneficial properties of biomass to increase the availability and reduce the costs of bioenergy and bioproducts while cleaning up water resources, enhancing soil health, and providing other ecosystem benefits.

The purpose of the Bio-Restore Workshop was to bring together experts to discuss the current state of the technology and to identify data and R&D relevant to the bio-restore concept. Specific topics included using dedicated energy crops and other biomass sources to provide environmental benefits, implementing algae technologies (e.g., wastewater treatment, direct bloom harvest, turf scrubbers, macroalgae), quantifying and valorizing ecosystem services, developing low-cost sensors and data management systems, and integrating “bio-restore biomass” with supply chain needs.

For the purposes of the workshop, the term “bio-restore biomass” refers to terrestrial and algal biomass that provides environmental benefits when produced or harvested. For terrestrial biomass, this primarily includes energy crops (herbaceous and woody), other cellulosic biomass, and waste biomass. For algal biomass, this includes wastewater treatment algal biomass, algal blooms, algal turf scrubbers/attached growth systems, and macroalgae. Types of biomass not of interest to the workshop discussions include oilseed crops, crops generally grown for food or feed, and algae grown in artificial light conditions or other energy-intensive cultivation designs.

2 Workshop Overview

The workshop opened with a presentation from BETO to provide context on DOE's mission, existing work in terrestrial and algal biofuels, and the goals of the workshop. Key presentations by federal agencies, national laboratories, and industry followed, providing overviews of terrestrial and algal sources for bioenergy, associated ecosystem services, and examples of bioproducts. Specific topics included the potential use of harmful algal blooms as bioenergy feedstock, data solutions and value capture, tools for assessing carbon dynamics, the production of consumer products, the use of algae for remediation of runoff, ecosystem services and their economic value, and landscape design. Additional presenters from academia, government agencies, industry, and national laboratories then gave 5-minute presentations on a range of related topics.[1] See Appendix A for a detailed workshop agenda.

After laying the foundation of the state of technology through these presentations, attendees were divided into breakout groups for BETO-facilitated discussions. The breakout groups were organized as three groups focused on terrestrial bioenergy and one group focused on algal systems. Breakout discussions and oral closeout reports took place during the afternoon of the first day and the morning of the second day, with summary conclusions of each breakout group presented to all workshop participants. ThinkTank, a collaborative online tool to facilitate real-time collection of ideas, was used by all participants during the breakout sessions to capture their input on discussion questions.

2.1 Breakout Session Summaries

Discussion questions were provided to the four breakout groups, each with about 15 participants, to promote dialogue. Questions during the first breakout session focused on defining the various biomass options, describing the state of technologies, and discussing the costs and values of bio-restore biomass. During the second day's breakout session, questions dealt with data and R&D needs and opportunities.

This report is organized with independent terrestrial and algal sections that cover the outcomes of the breakout session discussions. The key discussion points are summarized in the following sections and represent the views of attendees and not necessarily those of DOE.

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[1] With the permission of the speakers, presentations are available online: https://www.energy.gov/eere/bioenergy/bio-restore-workshop-presentations.

3 Terrestrial Biomass Breakout Session Summaries

The terrestrial breakout groups discussed the various terrestrial biomass options as well as current and developing technologies related to bioenergy crops, the associated cost factors, demand analysis, valuation of ecosystem services, cultivation approaches, sensor usage, information needs, and approaches for improvements.

3.1 Biomass Options

Terrestrial biomass options for bio-restore biomass include a variety of alternatives, many with geographic or other situational qualifiers. The plant type generating the most interest is switchgrass, which ranges from northern Mexico to southern Canada (and is found especially in the U.S. Midwest and Southeast). Specific species/cultivars (lowland vs. upland) can be selected to maximize productivity. Switchgrass, a native perennial, provides ecosystem services such as improved water quality, reduced nutrient runoff (e.g., nitrogen, phosphorous), improved water absorption in soils, increased landscape-level biodiversity, wildlife habitat, reduced soil loss (from wind and water erosion), reduced greenhouse gas (GHG) emissions, improved soil health, increased carbon sequestration relative to row crops, improved soil quality, flood mitigation, and aesthetic diversity of the landscape. Switchgrass can be placed in marginal land, riparian buffers, saturated buffers, prairie strips, utility rights-of-way, and dedicated farms. No irrigation is required, although it may be needed during establishment. Miscanthus, which shares many similarities with switchgrass, was also discussed.

Short-rotation woody crops are another form of perennial bioenergy crop. This category includes shrub willow, poplar, eucalyptus, red cedar, and other possibilities. Key U.S. regions being considered for development/production are the Northeast, Southeast, and Pacific Northwest. Short-rotation woody crops may provide a range of ecosystem services similar to those provided by switchgrass, as discussed above. Appropriate genotypes can be drought tolerant and resistant to pathogens. The trees are useful in poorly draining soil, require low nutrient input, and have little need for herbicides/pesticides. They have the potential to sequester metals and carbon and to increase soil nitrogen retention. Plantations may be in riparian buffers or dedicated fields. They can provide riverbank stabilization and windbreaks, and they can improve soil fertility over time.

Prairie grass mixtures are another category, with ecosystem services similar to those of switchgrass. In particular, the strategic planting of prairie strips can deliver multiple ecosystem services compared to the adjacent corn-soybean croplands. The diversity of native prairie grasses may increase soil microbe diversity and thereby enhance ecosystem function. These grasses also provide pollinator habitat, a key function in many locations.

Biomass sorghum is an annual crop with potential for biomass production throughout the continental United States. It may have some advantages in semi-arid regions (e.g., Texas, Kansas, Oklahoma) because it uses less water than corn crops. It may also be applicable for regions incorporating fallow periods in rotations. However, fundamental data are very limited, and the associated crop management (annual tilling) exposes land to erosion. Biomass sorghum may require high nitrogen input. It has a high moisture content at harvest, necessitating additional processing. Ongoing work to perennialize this crop is primarily being performed by major land grant universities such as Iowa State University and Texas A&M University.

Other options include cover crops and invasive plant species. Cover crops (e.g., rye) can promote conservation across the continental United States. This crop is well suited for anaerobic digestion if it is harvested green. Invasive plant species (e.g., tamarisk tree in the Southwest and along western streams, Cogan grass) may also provide an opportunity across the United States, as their removal and use as a bioenergy source could provide economic support. The removal of an invasive species from an ecosystem allows there to be more water, nutrients, and light resources for native plant species.

Forest thinning could provide another source of biomass, especially in the West, Southeast, Northeast, and Northwest. The rationale for thinning includes fire management, water management, improved forest health and resilience to pests, improved salmon habitat, and improved native biodiversity in the understory. In the Northwest, thinning may increase summer baseflows and benefit salmonids where temperatures remain suitable. Thinning may improve habitat for the spotted owl and other threatened and endangered species. Residue from logging operations represents a similar biomass source.

Many of the bioenergy crop options offer increased resilience to climate-related changes in precipitation, temperature, and extreme weather. Many also can be useful for phytoremediation or bioremediation of industrial contaminants, primarily based on their deep, extensive root systems.

3.2 Current State of Research

Current research to support the bio-restore concept includes a range of projects conducted by national laboratories, academia, and industry.

Oak Ridge National Laboratory's (ORNL's) Center for Bioenergy Innovation works on the development of mixed bacterial/fungal consortia to enhance biomass growth, nutrient acquisition, and tolerance to abiotic/biotic stress. These microbes can lower the need for exogenous nutrient, pesticide, and herbicide application. The Center for Bioenergy Innovation has investigated beneficial plant-microbe interactions to achieve enhanced water and nutrient utilization in switchgrass and poplar. ORNL's research includes environmental supply curves and ecosystem services valuation of water quality improvements to produce total-value curves related to feedstock supply. ORNL also researches pesticide use for annual food/feed/biocrops versus cellulosic perennial crops. Climate modeling by the Center for Bioenergy Innovation predicts where various genotypes of poplar will be able to be grown.

ORNL performs exascale supercomputer calculations to determine genome-wide coevolution and epistatic architectures responsible for bioenergy, bioproduct, and sustainability phenotypes in poplar and switchgrass. Researchers also have performed exascale calculations to determine high-resolution climatype zones on Earth and have used explainable-artificial-intelligence-driven genomic selection to design new genotypes to optimize bioenergy output and to thrive in specific environments.

Argonne National Laboratory's project on ecosystem services and economic value (in Illinois, Iowa, and Kansas), for example, focuses on the use of marginal land for bioenergy crops. Numerous publications and analyses have demonstrated the benefits to water quality and other ecosystem services. Economically, this long-running study has demonstrated the value proposition of implementing riparian buffers to reduce nutrient loss and reduce the cost of fertilizer while producing biomass feedstock with reasonable profit margins. The Argonne National Laboratory phytoremediation site in Illinois, which has operated since 1999, has poplars and willows targeting volatile organic compounds and tritiated water in soil and groundwater.

Other work by national laboratories includes Lawrence Livermore National Laboratory's study of the rates of deep soil carbon accumulation under switchgrass versus conventional annual crops in a national-scale network of sites (Texas, Mississippi, North Carolina, New York, Michigan, Illinois, Wisconsin, Oklahoma, and South Dakota). The National Renewable Energy Laboratory is developing rapid near-infrared analysis of terrestrial feedstock composition relying on inexpensive portable sensors. Additionally, Idaho National Laboratory's Integrated Landscape Management analysis examines multicriteria site suitability for field selection.

The U.S. Department of Agriculture's Agricultural Research Studies (USDA-ARS) has conducted more than 20 years of research on terrestrial crops for bioenergy at locations throughout the Plains, Midwest, and Southeast. Crops include switchgrass, Indian grass, big bluestem, Napier grass, sorghum, and others. In addition, a watershed-scale experiment by ORNL, the U.S. Forest Service, and university partners evaluates environmental sustainability of loblolly pine as a short-rotation woody crop in South Carolina.

The University of Illinois at Urbana-Champaign (UIUC) hosted the Switchgrass V international conference in July 2019. The UIUC's Center for Advanced Bioenergy & Bioproducts Innovation has applied the eddy covariance method to determine water usage by Miscanthus, corn, soy, and sorghum at Urbana, Illinois, and Ames, Iowa. A new project led by UIUC is focused on field-scale biomass production of advanced switchgrass cultivars and associated ecosystem service measurements. Sites are in Illinois, Iowa, Nebraska, and South Dakota. Team members include Argonne National Laboratory, Idaho National Laboratory, USDA-ARS, Iowa State University, South Dakota State University, and Antares. The UIUC Energy Farm investigates feedstock production and ecosystem benefits comparisons among corn, Miscanthus, switchgrass, and prairie grass mixtures.

Additional university-led projects include:

- The State University of New York's College of Environmental Science and Forestry (SUNY ESF) has performed many small- and field-scale research studies relating to bio-restore concepts, including work on former industrial land remediation with woody crops.
- The University of Notre Dame studies the role of cover crops in reducing water quality impacts in the Midwest.
- Iowa State University studies Miscanthus in farmed wetlands in Iowa; has a biomass sorghum breeding program; and investigates prairie strips integrated into row crop fields in Iowa, Missouri, South Dakota, and Nebraska (called the "Prairie STRIPS" program).
- North Carolina State University studies Miscanthus in the southeastern United States.
- The Great Lakes Bioenergy Research Center, led by the University of Wisconsin, performs sustainability studies of various energy crops in Michigan.

Finally, the Antares-led Iowa Landscape Design project explores the use of switchgrass on areas of low return in possible combination with corn stover and cover crops to maximize a combination of environmental benefits (water quality improvements, increased biodiversity, carbon sequestration, Conservation Reserve Program income, hunting, etc.). AGgrowTech operates commercial Miscanthus plantations in Iowa, Maryland, and North Carolina as dedicated whole fields, not buffers.

3.3 Technologies Already Developed or Under Development

Workshop participants described sensor technologies addressing a wide range of parameters and scales of analysis. Remote sensing applications in particular are being extended to include more parameters and more crops. Sensor categories operate at varying scales. For instance, ground-level field sensors have differing resolutions. Unmanned aerial vehicles offer very specific and high-resolution data, but require a large time commitment. Aircraft systems capture large areas at a high resolution relative to the cost. On an even larger scale, satellite data measuring climate and land use can be sourced from the USDA, the National Aeronautics and Space Administration (NASA), and other agencies. Participants grouped examples of these technologies into categories approximating their levels of development.

A variety of already-developed technologies may continue to undergo improvement, such as soil-water sensors and surface water flow and water quality parameters, including those used by the U.S. Geological Survey at water monitoring stations. Participants also mentioned that tractor-driven sensing systems (Green Seeker, Veris system, and others) are available to determine fertilizer rates.

Technologies that are considered in the middle stage of development include drone-based or ground-level hyperspectral imaging remote sensing for biomass yield and quality. Although specific wavelengths for composition traits are not well understood for many crops/plants, a few Advanced Research Projects Agency-Energy (ARPA-E) projects are identifying hyperspectral imaging bands that correlate with plant traits of interest; these projects are correlating such bands with satellite imagery. Estimates of crop biomass from integrated satellite remote sensing and biogeochemical modeling (DeNitrification DeComposition), as well as soil/environmental outcomes, are not yet fully developed. Another technology in progress is near-infrared spectroscopy for feedstock composition and midinfrared spectroscopy to understand soil organic matter properties. Regional-scale modeling of herbaceous biomass crop water use and carbon dioxide sequestration technologies are advancing.

Early-stage technologies include advanced crop yield modeling using remote sensing data and yield monitoring of biomass crops. Even though very few "ground-truth" relationships have been determined to allow calculation of biomass from aerial imagery, this technology is promising. In addition, lightweight, portable near-infrared sensors for rapid biomass analysis are being tested on switchgrass, Miscanthus, corn stover, and wheat straw. These measure compositional components such as cellulose, xylan, and others. Unmanned aquatic vehicles can potentially measure water quality.

Pilot-stage technologies include a variety of research areas. An experimental neutron-scattering approach to create three-dimensional soil carbon maps in situ and nondestructively is currently being field tested, although use of a neutron source in the field could be problematic. The possible future use of these maps would be to certify carbon management practices for incentive programs. Root-imaging technologies, such as those being funded by ARPA-E, are in the pilot stage. Variable-rate corn stover harvest headers and variable rate tillage equipment have potential, too. Remote sensing can be used to measure the spatial distribution of stover removal, to evaluate nutrient management and downstream effects on water bodies, and to characterize forest thinning. Researchers may implement edge computing for analytics on avian imagery and sound recordings for use in biodiversity assessments. Other technologies include nano sensors to monitor water quality and L-band radar to sense soil moisture to some depth. Encapsulated microbial consortia for field deployment have been tested in the field for poplar and are currently being assessed for applicability across bioenergy and food crops. A range of web-enabled sustainability assessment tools are in their infancy.

In addition to the technologies listed above, other methods involve computer tool development, field optimization approaches, and economic analysis tools. These span mature, middle, and pilot stages.

A familiar tool from Texas A&M University and USDA is the Soil and Water Assessment Tool for biogeochemical modeling, with application in landscape design. The DeNitrification DeComposition software tool from the University of New Hampshire is at the mature stage, as well. At a similar level of development is the USDA's COMET-Farm agroecosystem conservation model. Idaho National Laboratory has developed middle-stage efficiency modeling of field and subfield operations. Workshop participants discussed feedstock logistics modeling and digital engineering capabilities that show material attribute impacts (quality) on preprocessing costs and reliability. Improved harvest equipment ranges from pilot stage to near commercialization and commercialized.

Argonne National Laboratory is currently in the pilot stage of developing a tool integrating geospatial technology, numerical models, and data mining techniques for marginal land classification and analysis in agricultural lands at various spatial scales. This tool will be tested in Illinois and developed in the next few years for the entire midwestern United States. Another pilot-stage technology involves the possible use of high-performance computing to analyze sustainability trade-offs and synergies across heterogeneous landscapes. An additional research opportunity is a supply analysis that identifies where ecosystem service benefits could be marketed. Integrated landscape management could add a biomass supply scenario analysis to assess the full potential economic and environmental benefits of a bioeconomy. Although DOE's *2016 Billion-Ton Report* (DOE 2016) on biomass potential does not capture feedstock-specific downstream benefits or externalities, these values could be assigned to account for competitive advantages of feedstocks in assessing potential supply.

3.4 Costs of Terrestrial Bio-Restore Biomass

Various costs are associated with the development of biomass. These include preproduction scientific analysis, the full range of agricultural operations, and the storage and processing of harvested biomass. Other factors include the cost savings associated with bioenergy crop types and the cost to develop a system for quantification of ecosystem services. These cost-related issues are listed in detail in the following subsections.

3.4.1 Costs of Producing and Managing Bio-Restore Biomass

Although costs are associated with a range of activities for biomass production, quantifying or estimating these costs is beyond the scope of this summary.

For production, there are costs for site preparation, including removal of existing plants. Local equipment/expertise may not be suited for biomass installation, so transportation of equipment could create an additional cost. Land cost, in the form of long-term rental agreements for perennial energy crop production, represents another consideration. Finally, the bioenergy crop—in the form of seeds or plantings—would need to be purchased in a sufficient supply.

Management costs may include herbicide and fertilizer. Harvesting and baling may involve the same equipment and expertise issues that occur during the planting phase. Harvest losses can be ~30% of biomass, depending on the crop. Finally, transportation of the harvest will have costs that depend on the distribution (spatial density) of supply and the location of buyers (biorefineries).

The size and shape of harvest areas can have a significant impact on field efficiency. The spatial relationships of field sites relative to each other can have a big impact on equipment and operator needs. Other costs relate to specific situations, and may include cover crops for a corn stover system or access roads for forest thinning. Economic factors may play a role as well; for example, there is an opportunity cost associated with income during establishment years and a Conservation Reserve Program payment reduction may be incurred for harvesting. The new Soil Health and Income Protection Pilot Program (known as “SHIPP”) is attempting to address this issue. In the absence of crop insurance, there is a cost associated with production risk. Fundamental research represents another cost, through the testing and development of feedstock varieties for specific locations (climate, soil type).

Avoided costs can be factored into the overall economics when making a conversion from annual grains to perennial bioenergy crops. These include the avoided cost associated with removal of nitrate from a water body as a treatment for drinking water, from not applying pesticide, from payments for ecosystem services (externalities), and from avoiding irrigation if changing from irrigated corn to rain-fed switchgrass.

The potential for public-private mechanisms for ecosystem payments was recognized and discussed at the workshop. However, there would be costs associated with this bio-restore concept. One cost is the development of quantification and verification schemes for ecosystem services. This cost would need to be integrated into the process of selling credits. Reducing this cost is critical for the grower to achieve the economic benefit. In addition, soil monitoring (sampling and analysis) would have an associated cost if soil benefits are considered part of the environmental value.

3.4.2 Logistics Costs of Using Bio-Restore Biomass

Additional factors related to logistics and the economics of scale would affect the cost of biomass production. Low-density feedstocks result in increased transportation costs and in-field bale handling. Processing, drying, grinding, and densification would reduce the transport costs. Logistical costs would also depend on biorefinery size versus transportation collection radius. This expense would improve economically as the industry develops. At the field scale, inefficiencies due to field geometries (e.g., integrated landscape design, perennial crop subfields on marginal lands) would affect the logistics of operations. Further logistical challenges with personnel, equipment, and other resources could result because of the timing of harvest/management/planting of biomass crops versus commodity crops grown by the same producer. Scheduling issues may arise if a harvest is planned for a time when fields are wet. Losses are possible during storage (e.g., spoilage due to moisture), necessitating advanced storage designs. Other potential losses may occur as a result of fire, drought, flooding, extreme weather events, and so on, and crop insurance may not be available for bioenergy crops.

3.5 Value of Terrestrial Bio-Restore Biomass

Biomass has value for a variety of actual and potential buyers, including potential purchasers of ecosystem services benefits. These buyers, their quality requirements, valorization approaches, and related factors are discussed in the following subsections.

3.5.1 Current and Potential Buyers of Harvested Bio-Restore Biomass

Numerous current and potential buyers would have interest in bio-restore biomass. These buyers represent a range of industries and possible uses. Energy, agricultural, and environmental sectors may purchase bioenergy (biofuel and biopower), bioproducts, or ecosystem services.

Energy-related users have interests in biofuel and biopower. Biofuel producers create energy for transportation. Biorefineries, such as lignocellulosic biofuel producers, stand to benefit from bio-restore biomass. Alternative jet fuel producers are another example. Biopower producers use biomass for heat and electricity. Heating facilities (boiler plants) in rural areas without access to natural gas currently have achieved only limited market penetration, but there is a possible near-term market opportunity. Other buyers include biogas and pellet producers.

Agricultural users also have interests in biomass. Biomass has value as poultry and horse bedding, and used bedding can be codigested with animal wastes. Additional buyers of biomass include users of compost or mulch and the mushroom industry. Apiaries may see the potential for co-location of flowering biocrops to further support bee populations.

Other bioproducts may attract potential buyers of harvested bio-restore biomass. Pulp markets and the biocomposite industry feed a variety of sectors. Manufacturers of paper or plastic substitutes and/or biodegradable dishware can create cellulose products to replace single-use paper/plastic cutlery, cups, and plates. Shoe or apparel and xylitol companies may also buy biomass for their products. Construction sites may purchase grass- or woodchip-filled soil erosion socks. Some investors may be interested in generating nanocellulose and nanocrystals, along with biofilms. There is potential for biochemical manufacturers as well.

Conservation and environmental users are most interested in the ecosystem services that bio-restore biomass provides. Water treatment facilities can participate in nutrient trading markets. Federal and state conservation institutions such as USDA-National Resources Conservation Service (NRCS), the U.S. Environmental Protection Agency (EPA), and their state counterparts have a clear interest in bio-restored biomass products, as well.

3.5.2 Biomass Quality Requirements of Buyers

Workshop participants discussed several compositional and socioeconomic quality requirements. First, there should be consistency in all aspects of composition, including carbohydrate content. Low variability should be established in parameters such as cellulose, hemicellulose, lignin, ash, glucan, and xylan. Moisture level and ash content should be low, whereas density of the biomass product should be high. The biomass should contain minimal amounts of weeds and weed seeds. Also, although these attributes are general rules, it is important to consider that final quality requirements should meet the in-feed specifications of the intended market.

In addition to compositional attributes, the breakout group provided qualifying information on practical considerations and socioeconomic aspects. For instance, many current markets for wood chips do not operate using quality metrics. If there are quality metrics, a buyer will need the capability to perform quick and inexpensive measurements of key parameters in the field or at the point of storage/sale to control quality in a meaningful way. Furthermore, buyers may require certain ethical standards. Social requirements, such as ensuring fair labor practices and fair wages, have to be fulfilled. Some companies desire to meet consumer demand for more "sustainable" products and may have relevant quality certification/standards. Participants mentioned that European countries importing bioenergy wood pellets from the southeastern United States have a variety of strict sustainability requirements to help ensure that there are no negative impacts to biodiversity, water quality, and other environmental aspects.

3.5.3 Additional Entities That Would Find Value in Biomass

Participants were asked about other parties that would find value in cultivating and/or harvesting biomass, excluding those listed above that would want to purchase the biomass. These stakeholders can belong to industry, government entities, and/or the general community.

The industrial sector may find value in cultivating and/or harvesting biomass for a myriad of reasons. For instance, some companies want to reduce their environmental footprint, but cannot change their own in-plant production processes. One way that companies can reduce their carbon footprint is through purchasing carbon credits. Coal-fired power plants may invest in this market. Electric utility companies may allot money for transmission line creation and maintenance. In addition to the bioenergy applications, biomass can be used for bioproducts. Other industries could utilize the coproducts derived from biomass processing for soil amendments and blasting media, to name a few. Moreover, the environmental quality improvements that result from bio-restore biomass add value for companies. Businesses with extra land on their sites could be eligible for tax credits. Industry and other landowners who are required to remediate contaminated land can use phytoremediation techniques to reduce pollution at a relatively low cost. Such conservation efforts improve water quality, which benefits downstream fisheries and related industries.

Various government entities may see the monetary worth in biomass. Workshop participants discussed three such examples. First, federal and state conservation institutions like the USDA-NRCS, the EPA, and their state counterparts have interest in biomass applications to improve environmental quality. Second, the fire service can produce biomass from fire break clearing. Third, municipal wastewater treatment facilities can rely on biomass to reduce nitrate levels in regional watersheds. In a trading scheme, this could result in lower treatment costs for the discharged effluent.

Community members benefit from the ecosystem services that bio-restore biomass provides, such as nutrient regulation and pollination. At the farm level, growers derive benefits from the barrier strips that intercept and utilize the otherwise lost nutrients applied on commodity crops. Because perennial grass is associated with increased numbers of wild pollinators, farmers who rent bees for pollinating their crops can improve their bottom line. On a larger scale, the benefits of bio-restore biomass extend across landscapes and waterways. Wildlife habitat promoters, like the Wildlife Habitat Council, advocate for responsible land use that supports biodiversity. Hunters, or those who rent out land for hunting, have vested interests in supporting wild animal populations. Furthermore, tourism and recreational entities see value in the cultural services that biomass provides; for example, water quality affects boating, swimming, and fishing. Improved water quality ripples from small-scale inland lakes, creeks, and rivers to the larger-scale Great Lakes (e.g., Lake Erie) and the Gulf of Mexico.

3.5.4 Valorization of Ecosystem Services by Terrestrial Biomass

Participants noted that payments to producers for improved water quality, improved biodiversity, and so on should come from communities that will enjoy those benefits. Upfront payments to externalize the cost may be key to adoption by producers. Standardization is needed so that monitoring requirements do not become too burdensome or cost prohibitive. Satellite imagery may play a role in this effort.

The monetary value of ecosystem services could be based on biomass feedstock value or on the environmental benefits provided by the biomass. For example, the monetary value could be based on reduced water treatment operations that result from the removal of nitrogen from the water supply by biomass, or it could be based on the value of remediating contaminated soil or groundwater (in the form of phytoremediation). In addition, farmers could participate in carbon markets and sell credits for the carbon stored in soils and aboveground biomass, although this type of initiative would require effective and affordable monitoring systems. Monetary value could also be based on the magnitude of climate change impacts that are offset by the transition to low-carbon bioenergy that simultaneously preserves critical ecosystem services.

A potential starting point for valorizing ecosystem services might be the *2016 Billion-Ton Report* (DOE 2016), which generated consistent national data sets related to GHG emissions, soil erosion, and water quality parameters associated with the biomass production scenarios explored in Volume 1 of the report. Additional ecosystem services that could be valorized include carbon sequestration, soil health, and biodiversity (e.g., habitat improvement, aquatic and terrestrial recreation, hunting, fishing, pollinator services). As an example, Argonne National Laboratory assessed a wide range of ecosystem services for an Illinois watershed with marginal land assumed to be converted from grain crops to switchgrass. The ecosystem services were valorized to estimate the net economic improvement to the watershed.

Another reference for valorizing ecosystem services is a study conducted by IHS Markit (IHS Markit 2019). The study focused on carbon, nitrogen, and phosphorus for carbon credits and water quality credits. A current estimate for the potential to improve conservation agriculture through ecosystem market credits is $13.9 billion, according to the Ecosystem Services Market Consortium.[2]

3.5.5 Existing or Emerging Environmental Markets Relevant to Biomass Production and Management

The breakout group discussed existing, developing, and potential markets relevant to the bio-restore concept.

Biomass production has obvious applications for low-carbon fuels. In addition to bioenergy, there are markets for alternative products to replace essentially anything made from carbon. Biomass can be used in the fiber industry; biochar is a resource for the horticulture industry. A variety of companies interested in low carbon use—like General Mills, Dannon, Nestle, or other companies wanting to meet sustainability goals—may seek sustainable certification labels for consumer products.

Markets related to other ecosystem services have growth potential. For example, markets for cultural services, such as hunting, fishing, and recreation, can be valued using revealed preference methods. Several nutrient-trading markets for water quality are operating in the Chesapeake Bay, the Ohio River Basin Trading Project, and the western United States. Water treatment facilities may be involved. The U.S. Climate Alliance has an interest in reducing GHG emissions while adding value to the economy. GHG reduction credits, like the Climate Leadership Council's carbon sequestration markets or California's carbon market and Healthy Soils Initiative, can expand the bioeconomy. Institutional investors looking to de-risk their investment portfolios in agricultural systems may develop these markets.

3.6 Data Gaps and Potential Barriers

3.6.1 Data and Information Gaps With Regard to Quantifying and Valorizing Ecosystem Services of Biomass

To establish a system for quantifying the ecosystem services provided by perennial bioenergy crops and valorizing those benefits, information gaps would need to be filled.

Field-related information needs include biomass composition data as a function of crop type, landscape position (riparian area or marginal land within agricultural fields), geographic location, and agronomic practices, among other factors. Having on-farm data for the various feedstocks on marginal land is especially important because bioenergy crops are more likely to be integrated in those areas. The inclusion of nitrate and pesticide leaching data could support marginal land analysis and classification. Although adding nutrients to bioenergy crop systems might be useful, any evaluation must involve analyzing yields, costs, and

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[2] For more information, see: ecosystemservicesmarket.org.

environmental impacts. Measurement methods for nutrient leaching, nitrogen loss via volatilization, GHGs, and other environmental variables must be efficient and at a sampling frequency to allow study of carbon/nitrogen dynamics. Although remote-sensing efforts can provide estimates of such ecosystem services, more ground-truthing is needed to validate data values. Moreover, data from large-scale and long-term monitoring of biodiversity, carbon sequestration, and GHGs are needed to represent changes over space and time. This data requirement includes the need for system-level emission measurements of gases such as methane and nitrogen oxide. An examination of the soil microbial community and its diversity could enhance current understanding of GHGs and carbon sequestration. Many other belowground factors require further study as well, such as nutrient uptake in the deeper root zone and deep-rooted perennials' relationships with water penetration, water-holding capacity, and improved soil structure. Belowground biomass production, spatial distribution, and stability over time should be explored relative to various plant types. In general, the field would benefit from a larger volume of case studies with measured results and peer-reviewed publications to establish a credible and defensible basis for quantifying the environmental benefits associated with one practice versus another (e.g., bio-restore versus baseline).

Significant information gaps exist related to economics and adoption. For instance, actual monetary values of ecosystem services must be quantified. A detailed framework on economic value for each ecosystem service by region is needed. Return on investment should be determined at the county, watershed, state, and national levels. Standards for ecosystem service monitoring and certification are not developed. As it pertains to adoption, workshop participants suggested an assessment of changes in stakeholders' attitudes, understanding, and willingness to accept the implementation of bio-restore systems. Stakeholders would include regulators, environmental groups, and landowners. To encourage widespread adoption, there must be more information on how to motivate U.S. farmers to produce bio-restore biomass in each region. Once farmers agree to manage a new biomass crop type, farmers and harvesters will require some training. A complete picture of bio-restore crops and their ecosystem services under future climate scenarios would inform decision makers.

Information and communication needs include data management and data sharing, along with outreach efforts. Promotional communications media would convey the results from studies in a way that a broader group of stakeholders could understand. Regulators, environmental groups, financial institutions, and other entities may accept bio-restore biomass after learning about the positive effects demonstrated in long-term studies.

3.6.2 Scientific Barriers to Biomass Systems Participating in Environmental Markets

At present, there is a general lack of understanding of the scientific barriers and a lack of robust markets. Participants provided a list of barriers, like the scarcity of long-term monitoring data of ecosystem services because most project funding is short term. Many other barriers related to improved monitoring techniques. For example, a means of measuring soil erosion at an appropriate scale does not yet exist. Measuring belowground biomass is often destructive and labor intensive. The development of sensors offers a potentially significant means of assessing biomass systems for monitoring biomass and aspects of ecosystem services. Sensors would have to provide fast, reliable measurements of GHGs, including carbon dioxide, methane, and nitrous oxide over appropriate timescales. One of the most cost-effective ways to collect data rapidly for analysis is the use of satellite remote-sensing-based algorithms. However, biomass yield and composition predictions using optical or radar-based systems are not as well developed as those for commodity crops. To address this barrier, partnerships with NASA, the National Science Foundation, U.S. Department of Defense, ARPA-E, and/or the National Oceanic and Atmospheric Administration could enable collaboration on a Funding Opportunity Announcement to establish remote sensing relationships for heavily monitored sites. This multidisciplinary work to develop relationships between remote-sensed and ground-measured data could take place on USDA sites, Bioenergy Research Center sites, or BETO partner sites, to name a few. These types of scientific data would support the development of certification programs. A current certification system for GHGs and other field parameters does not exist.

Participants also discussed barriers associated with models. A mechanistic process in simulation models for realistic projections of carbon capture and storage is unavailable. In addition, the field currently lacks spatially explicit valuation tools for ecosystem services. The spatial/temporal extent of community benefits derived from ecosystem services is not well understood. Models that predict ecosystem services require improved resolution with validated data linked to specific georeferenced locations. A national-level assessment of ecosystem services, similar to DOE's *2016 Billion-Ton Report* (DOE 2016) that quantified economic impacts from perennial species, would provide a more complete picture of large-scale bio-restore biomass potential. Another question the group addressed is: to what extent will future climates affect ecosystem services? This uncertainty could affect models and lead to resiliency as a key criterion in future assessments.

There is not enough up-to-date information on how production practices can influence production to optimize environmental market access. An approach for increasing conversion efficiency and decreasing associated costs will be required to expand the market for bio-restore biomass.

3.6.3 Designing Research Projects to Overcome These Barriers and Enable Biomass Systems to Participate in Environmental Markets

R&D on the scientific barriers to bio-restore biomass systems would be a means to overcome some barriers and achieve more widespread adoption. Plans to continue long-term studies of ecosystem services and their effects would help build a larger knowledge base. To support broad-scale regional markets, there must be improvements in geographic/spatial toolsets for modeling and valuation. Models should predict the effects of future climate on the ecosystem services provided. Other barriers relate to the limited monitoring of nutrient dynamics; many questions about nutrient cycling remain. The development of low-cost, robust sensors could serve as one way to answer some of these questions. Eddy flux towers could be used to determine total carbon balance. Research on residence times can be accomplished with applied carbon and nitrogen radioisotopes. It is important to note that models that predict ecosystem services will also require validation via field ground-truthing. This effort would include new approaches to soil carbon modeling, and the role of plant-microbe interactions on soil carbon sequestration and soil nutrient cycling should also be examined. Analyzing water resources, water quality, and the water footprint in biomass systems at the regional level would also be of interest.

Collaboration can help overcome barriers. First, repositories and integration of existing data could collate all known information. The ecological-economic community should conduct peer reviews to validate research. It is important to have an independent validation of ecosystem services provided by field systems. Multidisciplinary research projects—including active collaboration with producers and industry—require stakeholder engagement and proof of concept. Engagement with farmers can support the measurement of field parameters as more monitoring on commercial-scale farms is needed. Partnerships with large companies that are engaged in "green" initiatives, such as carbon reduction targets and renewable energy goals, may support more bioenergy and bio-restore opportunities. Nevertheless, a consistent approach will be essential to processes supporting the production, marketing, and buying of carbon credits, both regionally and internationally. Joining with other agencies can aid in the development of outreach and educational materials. Community outreach programs can improve access to best practices for biomass management; they also help with public and policy education efforts.

3.6.4 Key Data Repositories

Biomass and ecosystem services data collected at pilot- to full-scale bioenergy research sites should be assembled and maintained as data repositories. Current data sources include Figleaf, github, Ag Commons, and BetyDB. SUNY ESF uses Dataverse. The National Corn Growers Association has a database with a "what-if" analysis capability that may be available for use by DOE and its projects/partners; there is a possible opportunity to implement this capability on the new BETO supercomputing capabilities. The Bioenergy Feedstock Library at Idaho National Laboratory is an existing repository of data on biomass feedstock sample quality.

Examples of well-managed, large R&D data sets outside of the bioenergy arena include the NASA Distributed Active Archive Center for biogeochemical data (Wilson et al. N.D.), DOE Atmospheric Radiation

Measurement for atmospheric data (ARM N.D.), DOE Office of Science Climate and Environmental Systems Science data (ESS-DIVE N.D.), and the National Atmospheric Deposition Program weather data repository (NADP 2019).

3.7 R&D Needs to Advance the Bio-Restore Concept

To make advancements in the bio-restore concept, R&D needs in general include well-defined and reliable data sets at sufficient spatial and temporal resolution to inform decision-making regarding ecosystem services, biomass production, and economic value. In addition, a defined set of standards needs to be developed for monitoring soil health by region, water needs or quality, air quality, biological diversity, and so on. Testing methods (sensors) to meet industry needs/requirements are also needed.

Specific research needs include seasonal biomass data for potential feedstocks at the genotype or advanced line level; cost estimates for fixed and variable costs, including costs for agronomic, insect, weed, and disease management; and control decision criteria for each management component. Economic research should be conducted on the viability of biofuels, biopower, and bioproducts (1) without ecosystem services payments versus (2) with ecosystem services payments. In addition, logistical analysis (flexibility in harvest, less frequent planting, fewer pesticides and fertilizers) would facilitate the growing of perennials, whereas research in field methods should be conducted to determine cost-effective harvest (generally from smaller patches that are scattered across the landscape), storage, and delivery of biomass while maintaining quality. These R&D needs are explored in the following subsections.

3.7.1 Necessary Improvements in Cultivation

R&D could reduce costs related to cultivation. R&D projects dedicated to particular crops, best management practices, and versatile field equipment can potentially improve cultivation. More robust crops would continue to thrive with various light requirements or weed competition. Accurate estimates of requirements for various agricultural inputs would reduce costs related to bio-restore crop development. An assessment of crop water usage could depict a crop's reliance on precipitation rather than irrigation in semi-arid areas. Landowners could potentially plant bio-restore biomass to reduce irrigated acreage and conserve groundwater. Farmers could reduce both fertilizer and pesticide use. Informed fertilizer management helps ensure adherence to nutrient loss reduction strategies. Farmers should consider reducing pesticide application and avoid using pesticides near tile inlets or riparian areas. Potential synergies exist with low- and reduced-till agriculture, soil conservation, and biochar. R&D projects may study timing considerations because planting and harvesting dates can affect species. Polyculture landscapes necessitate the use of field equipment for planting multiple feedstocks in multiple terrains. To optimize the application of results, trial locations should be based on existing breeding frameworks (e.g., yield gaps analysis, technical extrapolation domain). In addition, summarizing research into cultivation and management guidelines for different bio-restore approaches would have wide applicability. For example, there are guidelines for establishing riparian buffers from the USDA and others; however, these guidelines will need to be updated and modified if harvesting in these systems becomes a standard part of a bio-restore practice.

3.7.2 Necessary Improvements in Harvesting and Logistics

The breakout group considered improvements in harvesting and logistics to enhance overall performance of the bio-restore concept. For instance, R&D must find solutions for harvesting in wet soils and avoiding tile drainage. Researchers may enhance understanding of in-field efficiencies related to field geometry. As landscape designs incorporate bio-restore biomass in small and scattered areas, developers need innovations in harvesting technologies to increase efficiencies and minimize losses. Harvest can be optimized through yield-monitoring equipment for bioenergy crops along with decision-making tools and systems for managing herbaceous biomass systems. Other logistics improvements relate to transportation and storage. For instance, field-side densification can reduce transportation costs and improve storability. Moreover, on-site storage facilities that provide an anaerobic environment would reduce storage costs and respiration losses.

3.7.3 Necessary Improvements in Feedstock Quality and Characterization

Further improvements in cost and usage of bioenergy crops could be achieved in a number of ways. Spatiotemporal modeling of biomass quality attributes at a subfield scale would support advanced harvest and collection systems and could be leveraged to make residue collection more sustainable. A detailed understanding is needed about how cropping methods, soil composition, and other inputs influence feedstock composition.

The ability to predict feedstock quality prior to harvest, including moisture content and nutrient content, would provide useful information. A commercially available rapid method or instrument for quality analysis would provide a practical approach to assessing feedstock quality; otherwise, it is difficult to verify the quality that a biorefinery desires. At a broader scale, high-resolution hyperspectral imaging and near-infrared methods could be developed to determine feedstock quality. In Europe, X-ray systems are used for quality analysis at energy plants, and the X-ray systems are calibrated for wood. These systems should be tested in the United States and calibrated for herbaceous feedstocks.

Finally, bioenergy crops could be designed not only for biofuels, but also for production of higher-value commodity chemicals.

3.7.4 Necessary Improvements in Monitoring

Monitoring would be useful for the bio-restore concept, from assessing crops and ecosystem services to assessing feedstock quality in the field and after harvest. Monitoring needs include better equipment and longer study timeframes.

There is a need for better and cheaper sensors for edge-of-field monitoring, in-field monitoring, and remote sensing of yields and feedstock quality variability. Environmental sensors could be integrated into farm equipment. For assessing ecosystem services, the field would benefit from drain tile inlet and outlet sensors. In addition, advanced drone-based sensing can be used to detect water quality adjacent to fields and at key points in river networks. Researchers may improve quantification of nutrient fluxes within crops along an upland-lowland gradient. There is a need for approaches that quantify soil carbon persistence and are validated against radiocarbon data. Instruments for rapid quality analysis that are field deployable and could be used in a production facility should be capable of measuring ash, moisture content, and sugar content.

Studies over a broader timeframe would provide a more holistic representation of the bio-restore biomass system. Research should involve longer-term field studies through multiple rotations of feedstocks and comparisons to baseline conditions. Moreover, studies may monitor systems before, during, and after installation to assess their effects, or monitor adjacent systems that are not implementing a bio-restore approach.

3.7.5 Other Areas for R&D

Other R&D efforts beneficial to the bio-restore concept could be conducted in areas that do not fall into the previous categories. Saturated bioenergy buffers could arguably be the most effective multifunctional landscape in the Midwest to provide biomass, reduce nitrogen losses from tile-drained systems, and provide other ecosystem services. With this in mind, more field trials should be conducted, including some to make determinations of the optimal design for the size of a bioenergy crop's saturated buffer relative to the size of an adjacent field. In addition, field trials should examine multiple potential conservation practices together (e.g., saturated buffers and winter cover crops) to detect whether effects are additive or not. Studies may determine location suitability of different plants and how agroforestry applies to short-rotation woody crops. Observatories for soil carbon sequestration would contribute to soil carbon research. Social science aspects must also be investigated. The bio-restore biomass concept could be more widely implemented with a better understanding of what drives landowner decisions to produce bio-restore feedstocks. It is critical to find better ways to communicate potential benefits to the public.

3.7.6 Appropriate Metrics and Targets for Improvement of R&D Projects

Quantitative approaches should be used for assessing bio-restore research. The workshop group discussed a wide range of assessment approaches used to determine the extent to which bio-restore biomass provides ecosystem services. It is important that researchers obtain a comparison of metrics to the business-as-usual scenario. This applies to nutrient loading, soil carbon, GHGs, and species abundance. In other words, the percentage reduction in nutrient loading could be determined relative to previous land use. Nutrient leaching requires special attention to dynamics in both air and water. A 30% reduction target in nutrient loading relative to baseline is a conservative estimate related to the EPA's Gulf of Mexico Hypoxia Task Force findings. Because carbon stocks vary across space, metrics for soil carbon should be in absolute rather than relative terms (i.e., in Mg CO_2e ha^{-1} y^{-1} rather than a percentage increase) and should be regionally calibrated. Targets should be time dependent because carbon gains are expected to taper over time. R&D projects can include a percentage change in GHG emissions relative to business as usual. A measured percentage increase in species abundance relative to the previous cropping system may include studies on birds, pollinators, and belowground organisms (e.g., nematodes, fungi, bacteria).

Other socioeconomic metrics should be considered, too. The dollar value of ecosystem services across a biorefinery supply shed area could be calculated. The percentage reduction in feedstock cost when ecosystem services are valorized (relative to $84/dry ton delivered feedstock cost) should include a determination of the value of nutrient loss, carbon, and wildlife habitat. This cost aspect is not a cost reduction, but an offset. A cost per unit of nutrient removed by a system could be one component. Additional socioeconomic metrics and targets include realistic calculations of avoided costs and emissions relative to fossil fuel use. It would also be worth noting a percentage change in local jobs relative to business as usual. Public acceptance could be measured by the amount of time before a new biorefinery license is approved.

3.7.7 R&D Needs for Advancing Sensors

For the development of sensors to assist in the bio-restore approach, several capabilities and approaches are required. Advanced sensors should measure soil carbon, soil stocks (accumulation or erosion of soil), bulk density, roots within soils, and soil texture. A variety of sensors are needed to fully understand nutrient cycling, such as sensors for quantifying ammonia volatilization and deposition, measuring gas flux, and characterizing plant root/microbial interactions in the rhizosphere. Low-cost and field-deployable nitrate-leaching sensors would provide useful data as well. However, the trade-offs between the quality, scale of observation, and expense of sensors need to be better understood. There are questions regarding whether cheaper sensors should be deployed in large quantities and whether more expensive, high-quality sensors should be deployed sparsely. Mobile platforms such as unmanned aerial systems with sensor systems should be considered. Determinations need to be made about how the sensor readings correlate with the parameter of interest. Researchers should survey available sensors for the performance and grade of maturity.

3.7.8 Types of R&D Projects Needed to Advance Low-Cost Sensors

Research projects with a range of parameters of interest and types of equipment would enhance sensor development. One potential application includes using wildlife cameras, audio recorders, and associated signal processing to evaluate avian biodiversity changes. Methods to rapidly assess biomass quality would improve handling and logistics and reduce variability in the quality of biomass delivered to end users. Remote sensing for biomass yield and quality using an unmanned aerial system can be upgraded with lightweight sensors and sensors with fewer spectral bands. As remote sensing advances, multiple ground-truthing measurements will be critical for verifying data values.

Collaboration is an essential component of advancing low-cost sensors. Some of these collaborative projects may involve testing sensors for BETO at partner sites. There is a need for cost-effective, collaborative remote sensor projects that cover multiple crops and diverse physiographic regions. This effort should start "from the ground up" by having field plots and measurements (by universities or the USDA-NRCS) and utilizing the strengths of the multiple remote sensor platforms (e.g., field remote sensors, unmanned aerial vehicles, and satellite-based platforms) with involvement of the national laboratories for their data management and computing resources. The value of these types of collaborative projects can be realized through (1) development of cost-effective remote sensor algorithms specific to energy crops that could utilize relevant publicly available databases of satellite imagery, (2) identification of sites that could provide the ground-truthing needs for numerical modeling, and (3) more data for data-driven (artificial intelligence or machine learning) modeling needs, analyses, etc. Including those who are developing ecosystem valuation/certification systems during the sensor development process ensures that this information is generated as part of the sensor development process. Another cooperative effort could include an open consortium to design secure, reliable data acquisition electronic board designs that can attach low-cost sensors in a standard and reliable way. Electronic standards for security, connectivity, and so on could be developed as well.

3.7.9 R&D Needed to Advance Information Management Systems

Information management systems could be developed to support the bio-restore concept and related research. For example, Conservation Reserve Program baseline data do not exist at present. The scientific community could also benefit from a more rigorous USDA soil conservation plan based on detailed soil data rather than only the dominant soil type in an area. Breakout group participants mentioned that synergies must be developed among bioenergy research centers, BETO, and USDA-ARS regional biomass centers.

3.7.10 Information Management Systems Needed for Biomass Producers to Leverage the Value of Ecosystem Services

Information management for supporting ecosystem services valorization could be improved. Both growers and those developing ecosystem valuation/certification systems should be considered while building information management systems. For farmer-operators, participants suggested that full-suite systems with sensors tied to farm business management software suites would provide real-time decision support regarding quality, timing, yield, verification, etc. In addition, an auto-calibration system for yield monitors would help ensure that calibration is consistent for yield and quality measurements. The ability to generate spatial data on carbon, nutrient, water footprints, and online maps of the value of ecosystem services would provide feedback to producers. There are additional opportunities to develop spatially referenced databases for soils, climatic data (e.g., temperature, photosynthetically active radiation), cropping history, yield performance, and fixed and variable economic costs. For researchers, simplifying and centralizing many large existing data sets from individual projects could inform other projects. USDA data about past Conservation Reserve Program project efforts would aid in understanding the effects of perennials on soil carbon, for example. The discussion group noted that collaborative research with harmonized methods should include some guidelines to help ensure that those generating data have the right of first publication.

3.7.11 Types of R&D Projects That Could Advance Information Management Systems

Relative to the information management needs already identified, the breakout group considered projects that would fill data gaps. Diverse collaborations with representation from industry, government, academia, financers/buyers, verifiers, and conservation organizations must provide input on R&D processes, including application programming interfaces (or other interfaces) and information management system utilities. This field of study would benefit from an identification of standards for sharing bio-restore data. In addition, the development of big data platforms can facilitate data storage and sharing to calibrate sensors. It is worth noting that researchers working at DOE laboratories can leverage the LabKey effort in the Feedstock Conversion Interface Consortium. Research can broaden the understanding of high- and low-speed network connectivity throughout the nation, then determine the correct aggregated sensing solution for each situation.

A national-scale *Billion Ton*-type of study of feedstock production scenarios in relation to ecosystem services valuation would provide a setting of starting data for regional- and local-scale modeling efforts and projects. One effort already in progress is ORNL’s web-based Bioenergy Sustainability Tradeoffs Assessment Resource (BioSTAR) prototype tool for assembling national-scale data sets. BioSTAR can quantify baseline sustainability indicator data, which could be mapped to ecosystem services and could consider different feedstocks. Similar to what was accomplished in quantifying Conservation Reserve Program benefits in the 1990s, 2000s, etc., an overall value estimation of benefits that perennial crops can provide to the nation could be assessed using a combination of a prototype tool, such as BioSTAR, with existing economic valuations used by USDA-ARS, ecological economists, and others. These values would encompass ecosystem services such as nutrient reduction, wildlife habitat, pollinator habitat, soil organic carbon, landscape aesthetic, and water quality. Different timeframes (e.g., 2030, 2040, 2050) under different climate scenarios would be considered. Assumptions would be made for marginal cropland (e.g., high risk for erosion, flooding, marginally productive) only. The intent would be to avoid conversion of existing grasslands, pastures, forested areas, and wetlands.

4 Algal Biomass Breakout Session Summaries

Because algal R&D considerations differ from those of traditional agriculture, algae-based systems for providing ecosystem services were discussed in a separate group for the two breakout sessions. This group discussed the challenges and opportunities related to valorizing ecosystem services via attached growth systems, harvesting algal blooms, macroalgae cultivation, and wastewater treatment algae technologies.

Participants first framed the value of these ecosystem services to lay a foundation of the benefits of pursuing this research space. Next, the discussion focused on identifying the associated costs and detailing the challenges that need to be overcome to make the pursuit economical. Then, participants explained how applied R&D projects could address those challenges to lower the costs and to achieve the value of the ecosystem services. R&D portfolios must have a strategy formed by reliable data and analysis. The breakout group identified what data and information gaps must be filled by an analysis portfolio to guide R&D toward meaningful outcomes. The key points from these breakout session discussions are summarized in the following sections, representing the views of attendees and not necessarily those of DOE.

4.1 Value of Algal Bio-Restore Biomass

To assess whether ecosystem services provided by algae or the algal biomass itself have value, participants in the algae breakout group were asked a series of discussion questions to drill down into current and potential markets and the requirements of buyers within those markets. The breakout group came to a consensus that it is important to be realistic regarding the value proposition of nutrient-remediation algae. Low-cost inputs are unlikely to lead to high-value products.

4.1.1 Current and Potential Markets for Algal Biomass

The near-term market application for algae from nutrient-remediation sources is biofertilizers, soil stabilizers, and plant growth stimulants, which may allow for some synergies with terrestrial agriculture in achieving bio-restore objectives. Plant growth stimulants are any non-nutrient fertilizers that accelerate growth or increase crop yield (such as beneficial bacteria, humic/fulvic acids, plant hormones, and other compounds). Substantially impacted agricultural soils where salt content has made them nonviable for most crops can experience improvement from soil amendment treatments with algae-based organic content.

Other near-term market applications include power generation from anaerobic digestion or fossil fuel cofiring. Waste algae has been used for cofiring in biomass/coal power plants in India, although ash and nitrogen content may pose a concern. Aquaculture markets are also currently interested in algal biomass for fish feed due to protein, lipid, and macronutrient content. In addition, the company ALGIX has been successful in marketing the biomass for bioplastic resin applications such as footwear. ALGIX has contracts in place to purchase dried algal biomass at ~$1,100/tonne.[3] ALGIX works on a broad range of composite resins. Biocrude algal oil can also be converted into monomers/polymers. Some biomass fractions could be used for specialty chemicals, like those used in thermoset applications.

Other potential markets would be more difficult to access due to the variability of quality and composition of algal biomass from nutrient-remediation sources. One of the greatest hurdles for nutrient-remediating algal biomass is that, from whatever source, it would not be specially produced for products but as a waste coproduct with variable composition, quality, and availability, making any economic recovery challenging absent a high subsidy for production. High-dollar-value bioproducts, such as nutraceuticals, have high quality requirements. Even for fertilizer uses, regulatory safety rules require classifying some products as Class A or

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[3] ALGIX has purchased more than 1 million pounds of dry algae biomass at prices ranging from $0.05/lb up to $1.20/lb. The target market price for biomass is around $0.50/lb.

Class B biosolids, which do not have economically viable sale prices to overcome extraction and reprocessing costs, even at scale.

Overall, a primary concern for investors is that a large quantity of biomass must be reliably available before any market can develop, but a market will need to be identified before large quantities of biomass will be produced.

4.1.2 Algae Market Quality Requirements

As previously noted, algae markets have varying composition and quality requirements based on application. For example, municipal wastewater-grown algae is unlikely to lead to food products. For bioplastic applications, up to 40% ash may be acceptable and metals content is not problematic, although there are regulations on the percentage of certain metals allowed in plastics. For ALGIX resin, the quality requirements are >30% protein, <40% ash/mineral, very low lipid (<5%), and low carbohydrates (<10%). ALGIX also reports that low odor (which can result from burning or biodegradation/rotting) is a feedstock requirement, as quantified by gas chromatography–mass spectrometry.

Animal feed requires ensuring a lack of pathogens and toxins. Currently, testing for toxins in algal blooms is rare, and there are only a couple of laboratories that have the capability. It is estimated that the number of toxic algae blooms is higher than reported. Testing is an issue and needs to be further developed; it is a requirement for all food-grade products. Palatability and the nutritional value must also be considered, which vary based on the animal. Some toxins can be eliminated easily, but it depends on the biomass and the applications.

In most applications, at a minimum, biomass composition must be relatively stable for storage and transport logistics. Also important is the reliability of the quantity and consistency of supply. Biomass must be provided based on the customer production schedule. An outstanding question posed by the group is: how many months of production and composition analysis would be needed to convince a customer to build a process around this form of algal biomass?

4.1.3 Nonmarket Value of Algal Biomass

Although selling algal biomass after nutrient remediation may provide a revenue stream, the value of the remediation can also potentially help to lower the costs of bioenergy and bioproducts. Municipalities and communities that have excess nutrient runoff and/or general water quality issues would find algae remediation technologies valuable. Aquaculture farmers (e.g., shellfisheries) suffering from water pollution would benefit from algae remediation of cultivation waters. Tourism and water recreation industries suffer significantly from sargassum and harmful algal blooms—algae is destroying the quality of beach resorts. These industries would benefit from algae remediation or the direct harvest of blooms.

4.1.4 How to Capture Secondary Market Value

Valorizing ecosystem services provided by algae remediation is difficult due to the complexity of accounting for the economic impact of the harm of an impaired waterway. Economic impacts of impaired waters can be measured by fines for exceeding discharge limits, fishing days lost (or the number of shellfish harvesting days lost), days of recreation lost, or fishing licenses sold. Farmers and fishers can measure the displacement for electricity for running aerators and tally their copper sulfate/algae-cides costs. Algae blooms have caused significant personal and financial issues with residents in Florida and elsewhere. Recurring blooms can directly affect property values, and decreased property values can affect local property tax revenues. Municipalities have expended significant effort to manage blooms to respond to these issues. One workshop participant noted that their research has started to reveal that 1 meter of water clarity loss equals a 10% reduction in real estate value.

The algae wastewater treatment value proposition, especially in the face of increasingly stringent discharge limit regulations, is reasonably straightforward. Currently, municipalities in the Midwest pay $70–$150 per pound of phosphorus removed from wastewater. This payment can help offset costs of algae harvesting or production, and depending on the use, conversion into bioplastics or durable goods prevents the rerelease of the nutrients into the ecosystem.

A growing percentage of the consumer market wants products that are made sustainably and can address environmental challenges and liabilities. These green consumers see value in using renewable, waste, or recycled materials to make products. Attendees noted that millennials are a growing market force, and their "green-leaning" purchasing decisions are backed by market survey data. One discussion that emerged is a question as to who owns the algal biomass once harvested from a naturally occurring algal bloom. Currently, the biomass is of negative value, but an emerging market could turn the biomass from a waste into a product of positive value, and the "owner" would be in question. Municipalities may shift away from paying for cleanup. The current price of the biomass must be very low to meet logistics margins, and currently does not come close to offsetting the costs associated with direct harvest via dissolved air flotation. Uncertainty as to ownership, or willingness to pay for harvest, could affect future investors in commercial operations.

4.2 Costs of Algal Biomass Production

Although the production costs of nutrient-remediation may seem much lower than algae grown in specialized photobioreactors or large raceway ponds because water and nutrient inputs are more readily available, significant harvesting, logistics, and preprocessing costs still must be addressed. The breakout group outlined the costs associated with production of algal biomass from the four principle nutrient-remediation algae technologies of focus at the workshop: direct harvest of algal blooms, algal turf scrubbers, macroalgae cultivation, and wastewater treatment. Then, participants discussed the costs associated with processing the biomass into conversion-ready feedstocks.

4.2.1 Costs of Harvesting Harmful Algal Blooms

The current technology for harvesting harmful algal blooms requires pumping, chemically flocculating, and running dissolved air flotation through large volumes of water. The costs of harvesting algae blooms must factor in the on-average, very low concentrations; the sporadic and generally unpredictable nature of such blooms; and the relatively small amounts of harvestable algae in many locations. The cost of harvesting algae from blooms is a function of the concentration of the bloom, which is orders of magnitude lower in concentration than in an algae production pond. There are costs associated with setting up the equipment at a bloom location, which can move, and costs associated with bloom predictions, which are unreliable. Bloom forecasting is a research area that does not yet have enough data and information, and especially complicating this situation are the large variances of behaviors among algal species. The volumes of water to be treated rapidly becomes prohibitive. Harvesting algal blooms with current technologies is estimated to cost around \$0.10–\$0.15/dry lb eq. for the first dissolved air flotation stage/dewatering stage. Drying can cost an additional \$0.15–\$0.20/dry lb eq. Total algae harvesting/drying cost may be around \$0.25–\$0.45/dry lb eq. with added labor and transportation. In addition, respiratory toxins may be released during harvesting processes. AECOM conducted air quality monitoring during its bloom clean-up efforts and expects that increased regulatory scrutiny may come to bear in the future.

Ecologically, large-scale harvesting could disturb natural habitats and potentially affect the resting stages of blooms, which would complicate future bloom cycles. Risk assessments even on the primary producer community would be beneficial, because there could be unintended consequences at the microbial level. Another point the group considered is: if harvesting natural blooms becomes profitable, would companies be motivated to wait until blooms become large and disruptive rather than intercepting them at an early stage?

4.2.2 Costs of Turf Algae

In current attached-growth algae state-of-technology assessments, harvesting the turf from the liner is the primary cost because of the manual labor involved. Liners, which are engineered substrates to which the filamentous algae are attached, can also be high in cost. Other costs include the physical infrastructure of the flow-ways, the land, and pumping water. Habitat may also be affected where flow-ways are sited.

4.2.3 Costs of Macroalgae

Macroalgae cultivation requires engineered systems (or at a minimum, lines, buoys, and anchors), and there are seed hatchery costs (kelp gametophyte seed lines). Open ocean cultivation can be dangerous depending on the region and required fuel for marine vessels, as well as transport to and from the farms. Macroalgae cultivation near shore must compete with other shoreline uses (e.g., fishing, recreation, harbors). Desalination of dried seaweed for use as food adds substantial costs.

4.2.4 Costs of Algae Wastewater Treatment Systems

As with harvesting blooms, the costs of harvesting algae from wastewater treatment systems include flocculants, dissolved air flotation, and centrifugation. Current BETO-funded projects are estimating fuel from wastewater-cultivated algae to cost $11/gallon gasoline equivalent without any cost credits from the wastewater treatment, based on a 25-g/m^2/day annual average mixotrophic productivity and production of renewable natural gas from the digestion of the biomass. Additional nutrients, such as nitrogen, must be provided for some algae if specific biomass composition is required for product specifications. In addition, adding carbon dioxide enrichment can balance the carbon-nitrogen-phosphorous ratio to maximize phosphorous removal, but may not be necessary when the system can utilize mixotrophy if organic carbon is in the wastewater. Additional costs include the purchase of land adjacent to the wastewater treatment facility. Redundant remediation systems may be required to ensure consistent water quality output, as algae productivity is variable through diurnal and annual cycles.

4.2.5 Downstream Logistics and Conversion Costs

For any of these systems, there are costs that are associated with storage, transport, processing, and conversion into final products. Biomass must be characterized and assessed for quality against end-product specifications as well as stability. Seasonal productivity variation may require significant biomass storage operations. Algal biomass can decompose/rot during storage or may be subject to growth of unwanted microbes (e.g., bacteria). Using lactic acid fermentation of the carbohydrates in the algae can reduce decomposition and allow longer-term storage and transportation. Peracetic acid dosing is also a simple and effective way to dramatically increase shelf life of wet algae slurry/waste before final drying; the cost is about a $0.01/dry lb. Shipping costs for algal biomass are estimated at around $0.07/dry lb, and typically $0.10/mile by truck in the United States. Shipping wet biomass even over short distances or dry biomass over longer distances may be cost prohibitive.

Processing and conversion costs are typically relatively minor when compared to the costs of algal biomass production. Processing algal biomass into conversion-ready feedstocks requires energy for drying, unless it can be solar/air dried effectively. Drying is the primary cost driver to delivery of stable algal feedstocks and is usually in the $0.10–$0.20/lb range. Ash and metals may need to be removed and would be subject to disposition, depending on the end product. Bioplastic conversion requires a high capital expenditure (i.e., in the range of $10 million to build out a factory) but also involves relatively lower operating expenses (~$0.30/dry lb). Additional costs for consideration include packaging, warehouse space, quality assurance/quality control, and labor.

4.3 R&D Opportunities

On the second day of the Bio-Restore Workshop, the algae breakout group discussed how BETO-funded, applied R&D projects could address some of the costs identified by the discussion on the first day to take advantage of the value proposition of nutrient-remediation algae. “BETO-funded applied R&D” in this context was defined by the session as projects managed through cooperative agreements between BETO and an outside partner to conduct R&D addressing a specific technical barrier and working toward improvements to overcome that barrier. The discussion followed a generalized supply chain for algal bioenergy and bioproducts production, identifying necessary improvements in each component that could be addressed by strategic R&D.

4.3.1 Necessary Improvements in Biology

Toxins can be a persistent concern in algal biomass. R&D is needed both to decrease toxin content through methods such as microbial degradation and to evaluate toxin destruction during conversion processes such as hydrothermal liquefaction. Algae biomass can be lost to grazers, although this is a bigger problem in purpose-grown monocultures; better understanding and manipulation of interactions among different species can help to protect algae crops. Improving biomass composition in favor of product specifications (e.g., increased lipid content, prevention of overaccumulation of biogenic ash) can help to improve biomass value. Algae can be rationally selected to remediate particular waste profiles and improve nutrient use efficiency and biomass yield. The field would benefit from a complete picture of an algal phenotype derived from epigenetic characterization of genes by environment interactions.

For systems that harvest harmful algal blooms, better indicators of bloom prediction based on characterization of molecular mechanisms underpinning bloom physiology are needed. Improvement of detection and assessment methods for algae cells, toxins, and metabolites are required to make them faster, cheaper, and capable of higher throughput. For wastewater treatment systems, identifying strains with high productivity in compromised waters is important. Research projects can capitalize on mixotrophic algae to utilize/remove organics as well as nutrients from wastewater, while improving productivity.

4.3.2 Necessary Improvements in Culturing and Ecology

The ecology of the algae culture can have significant impacts on productivity, product yield, and stability. Areas for R&D include optimizing stoichiometry, nutrient cycling, and complex microbial communities for algal biomass growth. Ecological research can also support identification of the most promising locations for bloom harvesting or algal turf scrubber deployments. Algal and terrestrial bioenergy systems could also be coupled to achieve remediation/restoration outcomes by applying algae to soil to improve quality and increase plant productivity. The ecology of cultivation systems will need to be evaluated to ensure that there are no downstream pollutants and/or toxins released into the watershed and that there are no negative impacts on natural food webs.

Attached algae cultivation (turf algae) has the potential for additional bioremediation services other than just removing nitrogen, phosphorus, and metals. Examples include reducing total organic carbon, biological oxygen demand, and coliform. There may be other algae cultivation strategies that have similar or unique benefits. Although turf algae benefits from a reasonably long history in remediation, it lacks fundamental study at lab and pilot scales under controlled environments that could produce more precise results to advance the technology. In addition, engineering design projects can develop cost-effective cultivation systems targeting different wastewater applications; cultivation systems will have different designs and treatment goals if they are installed for secondary or tertiary treatment, or both.

4.3.3 Necessary Improvements in Harvesting

Harvesting costs are significant in nutrient-remediation algae, and low-chemical, low-energy/passive systems will need to be developed to bring down the logistics costs of delivering algal biomass. Applied R&D algae projects will need to utilize real-time data and automated heuristics to optimize harvesting, avoid culture crashes, and increase biomass yield. Harvesting systems will need to be improved to be more selective to reduce potential impacts on nontarget organisms. Harvesting that relies on flocculants poses potential environmental impacts (e.g., if flocculants are aluminum-based chemicals) and the chemical costs per mass of algae removed or gallon of water treated will need to come down. Gravimetric harvesting of algae grown on wastewater without chemicals currently requires a 2- to 24-hour settling time to enable harvesting 90%–95% of the algae consistently. Harvesting systems could also be improved to address saline systems. High ash and salt concentrations will pose an environmental impact and/or deposition requirement. Use of electrocoagulation as a harvesting system could be well suited to saline applications.

4.3.4 Necessary Improvements to Transport and Storage

There are significant questions regarding supply chain and distribution systems for nutrient-remediation algal systems. Buyers, especially those looking to capitalize on the environmental sustainability of the algal feedstock, would require the ability to trace the supply chain and life cycle GHG emissions through a verification system. In addition, throughout the supply line, transportation and storage can affect the composition of algal biomass, and macronutrients and chemicals of interest can be lost. R&D will be needed to ensure that these beneficial components are not lost and are potentially maximized through containment strategies.

Supply chain logistics will need to identify appropriate co-location of resources, such as waste nutrients. Future algae supply chains could follow current BETO models, which consider large farms co-located with conversion facilities, per system design. This model will be more difficult to implement with distributed scales, for example, in systems where algae ponds line farmlands to collect runoff or at wastewater treatment plants. These systems are distinctly different from the open-raceway pond model, and space for conversion facilities could compete with primary facility operations.

4.3.5 Necessary Improvements to Conversion

Although participants previously noted that conversion processes are not nearly as expensive compared to the costs of cultivation and harvest, there are still significant areas for improvement, which can be addressed by applied R&D projects. Conversion processes that can address and eliminate toxins, such as heat treatments, will be required when dealing with harmful algal blooms or other algae systems that have toxic potential. In addition, systems will need to focus on how to address high ash and problematic metals to “upgrade” the biomass to conversion-ready feedstocks. Hydrothermal liquefaction is often cited as being a viable algal biomass-to-fuels conversion process for biomass that is of low quality; however, existing BETO-funded models illustrate that even moderate ash content drives up the costs of conversion, and less expensive methods for cleaning up the hydrothermal liquefaction aqueous phase are still required to achieve a competitive per-gallon price.

R&D is necessary for precise control and design of the conversion process to obtain the target products at high yield, and to identify additional high-value products that may be viably recovered during the conversion process. R&D on end products would help to provide data for purchase agreements. For example, algae have potential as a plant stimulant, but there have not been adequate field studies to test the efficacy of the application, only lab-scale tests in controlled environments. There are also opportunities to leverage existing conversion infrastructure and equipment, such as aerobic digesters, ethanol plants, and composting facilities. Using existing and under-used infrastructure could help to reduce logistics costs and increase the rate of deploying algae technologies. Examples of potential synergies with other renewable power systems include the mixotrophic incorporation of food waste and the offshore production of macroalgae that may present synergistic opportunities with hydropower production facilities.

4.4 Data and Analysis Opportunities

After the algae breakout group discussed areas where BETO-funded applied R&D projects could reduce the costs of algae systems, the group reviewed how a BETO-funded data collection, modeling, and analysis portfolio may also support these systems. The group identified the data, information, and analysis needed to close information gaps in establishing commercial bio-restore algal biomass production systems.

4.4.1 Data Needs

In order to develop these bio-restore algae systems, data are needed on a range of research areas. Specifically discussed was omics data (e.g., genomics, proteomics, or metabolomics) correlated with growth, as well as for harmful algal blooms and toxin production. In situ, species-specific measurement of processes of interest (e.g., nitrogen or metal incorporation, toxin production/degradation), as well as species interactions for these processes, were also discussed. The algae grown in these conditions will also require biomass compositional data and elemental content collection to determine product suitability.

Water quality data on natural water bodies would also help to identify available resources. In general, data are often available at wastewater treatment facilities (although data access may be limited); however, the water quality of lakes and rivers are more variable seasonally and more sparsely monitored. Nutrient flux as a function of season/weather is not well understood, although nutrient flux from cropland runoff can be reasonably simulated using ecohydrological models. In addition to nutrients, data on the microbiomes associated with surface waters and waste streams as well as bloom monitoring data in space and time in regions of interest also could support feasibility assessments where algae will be most productive. The EPA already has an accessible geographic information system (GIS) data set of wastewater treatment facilities that can be cross-referenced with land parcel maps to automatically identify potential sites for algae production, and satellite imagery can be automatically integrated to identify sites with accessible land on-site or adjacent to a site (usually municipally owned) that are not already built. In addition to identifying systems with comprehensive monitoring data (e.g., nitrogen, phosphorous, micronutrients) for assessment of project feasibility, baseline environmental/ecological “health” data would help to guide restoration efforts.

Data can also help to valorize the algal remediation services. Economic data on the costs of harmful algal blooms to municipalities and sectors such as recreation, property values, drinking water safety, and the current costs of bloom response and mitigation efforts can help to frame a cost-benefit analysis of utilizing bloom harvesting systems or upstream remediation systems. Furthermore, data are most beneficial to the R&D community when access is open. Nonproprietary open-access application programming interfaces for integration of data sets will provide better automated and replicable analyses. An algae data working group could help to build interoperability/specifications that would allow all BETO-funded software development to work with as many data sources and products as possible.

4.4.2 Information Needs

Metadata, such as operational information, are frequently not included in published data sets and can significantly affect analysis and interpretation of results. Participants also noted that information to support facilitating partnerships would be beneficial, such as a list of companies and projects related to this topic space, municipalities interested in partnering, and major point sources. Information needs to be provided to inform approaches that would make agricultural landowners interested in partnering in algae projects.

4.4.3 Modeling and Analysis Needs

Modeling can help turn data into actionable information for project teams and decision makers. For example, data on nutrient flux can be modeled as a function of weather events, and machine learning from environmental data inputs (from in vitro and ecological assessments) can help to predict harmful algal blooms. BETO frequently leverages techno-economic analysis, life cycle analysis, and resource assessments in strategic planning efforts and to support decisions on R&D milestones. These analyses can help to define suitable metrics for bio-restore algae production, such as including the economic life cycle benefits of nutrient reductions. A resource assessment of harmful algal blooms (e.g., location, frequency, extent) can help to determine whether there is enough biomass potential to warrant significant investment. Obtaining a cost-benefit analysis of conservation practices versus some bio-restore algae systems would be important to understand the unique advantage of these projects compared to other options, such as large-scale farmland conservation practices. Conservation practices can reduce nutrient runoff from cropland, but effects can be limited, especially when tile-drainage (subfield drainage) is employed. Comparative analysis can also help to weigh algae systems against one another.

5 Conclusions

Participants’ comments focusing on specific ecosystem services under a bio-restore concept generally targeted carbon sequestration or nutrient (nitrate) loss reduction. However, other comments included a wider range of ecosystem services, such as biodiversity (microbes and insects; birds and mammals), hunting, habitat improvement, aquatic and terrestrial recreational value, erosion reduction, soil health improvement, and GHG reduction. Other comments focused on the beneficial social and economic impacts that could be generated from a bio-restore land-use change. Switchgrass was commonly the focus of discussion, but other types of grasses, short-rotation woody crops, and other terrestrial sources of biomass were also identified. Discussion also confirmed that results from current and future field studies are highly valued. Finally, participants described a wide range of current and potential buyers of bio-restore biomass or the associated ecosystem services of perennial crops.

With regard to algal bio-restore biomass, the breakout group came to a consensus that it is important to be realistic regarding the value proposition of algae from nutrient-remediation sources. Algal biomass from harmful algal blooms has low sale value, and harvesting it currently presents a significant cost. The products resulting from bio-restore efforts would likely be high volume and low value because of the variable quality of the biomass composition and the cost of harvest and extraction. Near-term products include biofertilizers and power from anaerobic digestion and, in certain circumstances, resin filler for plastics and foam applications.

In both the terrestrial and algal groups, participants identified the need for improvements in cultivation, harvesting, feedstock quality, feedstock characterization, and monitoring, as well as scientific barriers to adoption. Many comments dealt with a need to develop standards in data collection and data sharing. The goal of having such standardization in monitoring is to plan for an eventual need for the certification of ecosystem services. Certification for an ecosystem services trading or payment system is anticipated in the future, and buyers will need to have a clear and validated understanding of what they are purchasing.

Longer-term field studies are desired for increased understanding of biogeochemical changes resulting from perennial bioenergy crops, especially with respect to soil carbon (carbon sequestration).Technological advances are also anticipated. Participants showed a great deal of interest in the identification, development, and validation of sensor technologies for rapid assessment of ecosystem services parameters. These include ground-based, unmanned aerial vehicle, aircraft, and satellite technologies with application in the analysis of any of the ecosystem services. Participants in both the terrestrial and algal groups also expressed the need for the development of new tools, such as spatial tools for ecosystem services assessment and valuation at various scales.

Altogether, the participants’ input described the current status of the concept of bio-restore as well as the anticipated or desired future research, technology development, and tools to support the production of terrestrial and algal biomass while realizing environmental, economic, and social benefits. The continued development of such capabilities is key to adoption of bio-restore biomass generation.

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Appendix A: Workshop Agenda

U.S. Department of Energy Bioenergy Technologies Office Bio Restore Workshop				
Day 1 September 25, 2019				
7:30 AM	5:00 PM		Registration Table Open	
7:30 AM	8:30 AM		Coffee	
8:30 AM	8:50 AM	20	Opening Remarks from BETO	Kristen Johnson (BETO)
8:50 AM	9:05 AM	15	Harmful Algal Blooms as Feedstock	Alina Corcoran (New Mexico Consortium/LANL)
9:05 AM	9:20 AM	15	Data Solutions and Value Capture Propositions to Support Bioenergy Crops	Nick Goeser (Craigson Innovation Group)
9:20 AM	9:30 AM	10	Tools for Quantifying Carbon Intensity of Bioenergy Feedstocks Enabling Carbon-Negative Fuels and Carbon Farming	David Lee (ARPA-E)
9:30 AM	9:40 AM	10	Transforming Air and Water Pollution into Durable Consumer Products	Ryan Hunt (Algix)
9:40 AM	9:50 AM	10	Attached Algae for Coupling Remediation of Runoff with Biomass Production	Ryan W. Davis (Sandia National Laboratories)
9:50 AM	10:05 AM	15	Q&A Period	All
10:05 AM	10:20 AM	15	Break	
10:20 AM	10:30 AM	10	Bringing Ecosystem Services into the Equation	Yetta Jager & Natalie Griffiths (ORNL)
10:30 AM	10:40 AM	10	Assessing and Valorizing Ecosystem Services Through Field Research and Scale Up	Cristina Negri (ANL)
10:40 AM	10:50 AM	10	Landscape Design Toolset, Infield Practices	Kevin Comer (ANTARES)
10:50 AM	12:00 PM	70	**3x5 Presentations** • Energy, Climate Change, and Environmental Markets - Bill Hohenstein (US Department of Agriculture - Office of Environmental Markets) • Sustainability Research at Great Lakes Bioenergy - Phil Robertson (Great Lakes Bioenergy Research Center) • Tools for Tracking Conservation Practices and Outcomes for Ecosystem Services Markets and Supply Chain Reporting - Steve Hagen (Dagan, Inc.) • Current Research Status of Perennial Grasses for the U.S. Bioeconomy: USDA-ARS - Marty Schmer (USDA-ARS) • Pathway to Reduce Biomass Access Costs and Balance Logistics and Sustainability Outcomes in Agricultural Fields - Mike Griffel (Idaho National Laboratory)	Attendees

			• Integrating Shrub Willow Crops into the Landscape to Address Environmental and Community Challenges While Producing Bioenergy and Bioproducts - Tim Volk (State University of New York College of Environmental Science and Forestry) • How Does the Center for Advanced Bioenergy and Bioproducts (CABBI) relate to this Bio-Restore Workshop? - Emily Heaton (Iowa State University) • Unlocking Algae Genomic Potential with Epigenetic Keys - Christina Steadman (Los Alamos National Laboratory) • Near-Term Algal Biorefineries for Co-Production of Clean Water, Bioproducts and Biofuels - Shelley Blackwell (MicroBio) • Restoration Algaculture - Scott Edmundson (Pacific Northwest National Laboratory) • MiProbE: A real-time cloud-based microbial sensor platform - Evan Taylor (Burge Environmental) • Strategies and Technology for Growing and Processing Algal Biomass with Multiple Benefits - Shulin Chen (Washington State University)	
12:00 PM	1:00 PM	60	**Working Lunch:** We encourage you to use this time to network and connect with attendees.	
1:00 PM	3:00 PM	120	**Breakout Session One** Concurrent technical sessions focused on defining the biomass options, state of technology, and costs and value of "bio-restore" biomass.	Facilitated Discussions
3:00 PM	3:20 PM	20	Break	
3:20 PM	3:30 PM	10	Convene	
3:30 PM	4:30 PM	60	Report-out from Breakout Session One	Topic Chairs
4:30 PM	4:45 PM	15	Closing Summary from Day 1	Kristen Johnson
Day 2 September 26, 2019				
7:30 AM	8:30 AM	60	Coffee	
8:30 AM	8:35 AM	5	Convening of Day 2 (in breakouts)	
8:35 AM	10:35 AM	120	**Breakout Session Two** Continued technical sessions discussions focused on defining the data and R&D needs and opportunities.	Facilitated Discussions
10:35 AM	10:50 AM	15	Break	
10:50 AM	11:50 AM	60	Report-out from Breakout Session Two	Topic Chairs
11:50 AM	12:00 PM	10	Closing Comments and Meeting Adjournment	Kristen Johnson

Appendix B: Workshop Participants

The following is a list of participants who elected to share their contact information in these proceedings:

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