CONSORTIUM FOR CULTIVATING HUMAN AND NATURALLY REGENERATIVE ENTERPRISES

USDA-NIFA SUSTAINABLE AGRICULTURAL SYSTEMS AWARD 2020-68012-31824

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PROJECT SUMMARY

Title: Consortium for Cultivating Human And Naturally reGenerative Enterprises (C-CHANGE)

PD/PI:	Schulte Moore, Lisa	**Institution:**	Iowa State University
Co-PD/PI:	Richard, Thomas	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Roeslein, Rudi	**Institution:**	Roeslein Alternative Energy
Co-PD/PI:	Arbuckle, J. Gordon	**Institution:**	Iowa State University
Co-PD/PI:	Brown, Robert	**Institution:**	Iowa State University
Co-PD/PI:	Campbell, Alexis	**Institution:**	Iowa State University
Co-PD/PI:	Comito, Jaqueline	**Institution:**	Iowa State University
Co-PD/PI:	Heaton, Emily	**Institution:**	Iowa State University
Co-PD/PI:	Helmers, Matthew	**Institution:**	Iowa State University
Co-PD/PI:	Kimle, Kevin	**Institution:**	Iowa State University
Co-PD/PI:	Liebman, Matt	**Institution:**	Iowa State University
Co-PD/PI:	Mba Wright, Mark	**Institution:**	Iowa State University
Co-PD/PI:	Niemi, Jarad	**Institution:**	Iowa State University
Co-PD/PI:	Swenson, David	**Institution:**	Iowa State University
Co-PD/PI:	Thompson, Michael	**Institution:**	Iowa State University
Co-PD/PI:	Tyndall, John	**Institution:**	Iowa State University
Co-PD/PI:	VanLoocke, Andy	**Institution:**	Iowa State University
Co-PD/PI:	Zhiyou, Wen	**Institution:**	Iowa State University
Co-PD/PI:	Bansal, Saurabh	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Ciolkosz, Daniel	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Costello, Christine	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Fowler, Lara	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Gagnon, Mark	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Hill, Kathleen	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Hinrichs, C. Clare	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Hristov, Alexander	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Johnson, Matthew	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Karsten, Heather	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Kemanian, Armen	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Toraman, Hilal Ezgi	**Institution:**	The Pennsylvania State University
Co-PD/PI:	Schwartz, Thomas	**Institution:**	FDC Enterprises
Co-PD/PI:	Trabue, Steven	**Institution:**	USDA Agricultural Research Service

PROJECT SUMMARY

The Consortium for Cultivating Human And Naturally reGenerative Enterprises, or C-CHANGE, is a transdisciplinary partnership united in the effort to advance **a new biobased value chain.** This new value chain is based on the production of renewable natural gas (RNG) and associated bioproducts through the anaerobic digestion (AD) of herbaceous biomass combined with manure. It is expected to provide a sustainable income stream for agricultural stakeholders in the US Upper Midwest and Mid-Atlantic regions, where most of the nation's corn, soybean, hogs, poultry, eggs, biofuels, and large quantities of dairy are produced. RNG is the best-incentivized, fastest growing product in today's bioeconomy. The novelty of the project lies in leveraging a successful business model based on the AD of manure to encompass new agricultural feedstocks, more diverse products, and increased value throughout the supply chain. C-CHANGE provides integrated research, education, and extension activities directed toward feedstock diversification, modularization, process intensification, and stakeholder engagement to reduce supply chain risks, increase product value, and improve production, profitability, and sustainability. The pressing needs to alleviate social, economic, and environmental concerns associated with current agricultural systems, and to foster new economic development in rural America, drives the demand for C-CHANGE. More than 55 organizations have already provided input, helped refine project scope and priorities, and enlisted for demonstrations, deployment, and scale up. Once fully developed, the value chain will substantially contribute to national targets for biofuels and bioproducts while simultaneously meeting other goals promoting human health, economic prosperity, energy security, and ecosystem resources.

A. INTRODUCTION

Goal and Objectives

The overarching goal of the Consortium for Cultivating Human And Naturally reGenerative Enterprises (C-CHANGE) is to **advance a new biobased value chain** based on the production of *renewable natural gas (RNG) and associated bioproducts* through the *anaerobic digestion (AD) of herbaceous biomass* combined with manure (Fig. 1). We expect the value chain,[1] once fully deployed, will foster new economic development in rural America while simultaneously promoting farm prosperity, human health, energy security, and ecosystem resources. C-CHANGE will achieve its goal through integrated research, education, and extension activities directed toward modularization and process intensification to reduce risk, improve production and profitability, and generate valuable products and services along the entire supply chain. *C-CHANGE focuses on rain-fed, grain-based agriculture systems of the Upper Midwest and Mid-Atlantic US, rapidly expanding the use of AD as a linchpin technology.* These regions are home to 71 million people and produce most of the nation's *corn, soybean, hogs, poultry, eggs, and biofuel, and substantial quantities of dairy*.[2]

C-CHANGE addresses the interconnected challenges and opportunities facing US agriculture today with an integrated solution: we leverage AD and RNG and expand the technology to herbaceous feedstocks, reduce economies of scale, and develop associated bioproducts, thereby charting a practical and achievable path to both sustainability and economic development goals (Fig. 2). The **novelty of this work** is expanding the successful business model based on the AD of manure for RNG to encompass new agricultural feedstocks and more diverse products. RNG is the fastest growing and best-incentivized product in today's bioeconomy: since EPA approval in 2014, RNG has accounted for 97.7% of the 1.02 billion gal equivalents of cellulosic biofuels produced in the US.[3] However, assuring the future growth and resiliency of this new industry requires expansion of feedstocks beyond wastes and the development of new markets for products

Feedstock Production	Anaerobic Digestion (AD)	Co-product Processing	Distribution and Markets	Societal Value
• Herbaceous biomass, incl. perennial grasses, double crops, crop residues • Manure from swine, dairy, beef cattle, poultry • Food, processing wastes	• Single, 2-stage • Mesophilic, thermophilic • Pretreatment, co-treatment • Process intensification and automated control • Biogas (CH_4, CO_2) • Digestate (liquids, solids)	• Biogas separation • RNG* upgrading to liquid fuels and chemicals • On-farm cogeneration of electricity, heat • Solids separation • Drying, composting • Torrefaction, gasification	• RNG* and CO_2 for utilization, sequestration • Slurry fertilizer • Pellets, bedding and fiber, compost • Process heat, activated carbon products, biochar • Ecosystem services^	• Renewable products and services • Private and public revenue • Jobs • Healthy environments • Lower risk, lower cost, more resilient agricultural systems

Figure 1. A graphical representation of factors considered in C-CHANGE's biobased value chain. *RNG = Renewable Natural Gas, may be injected into pipeline or sold as Compressed Natural Gas (CNG). ^Ecosystem services include improved water quality, life cycle emissions, and nutrient use; wildlife and pollinator habitat enhancements are also expected.

from AD, while contributing to improved environmental performance of agriculture. We will assess the technical, economic, environmental, and social potential of: (1) utilizing herbaceous feedstocks in AD for RNG; (2) expanding the product portfolio of AD to include process heat, liquid fuels, electricity, biobased chemicals (methanol, polymers, latex paint, adhesives, lubricants, fertilizers), and other valorized co-products (fiber, bedding, compost, biochar, activated carbon, fuels); and (3) improving ecosystem services (clean air, clean water, soil health).

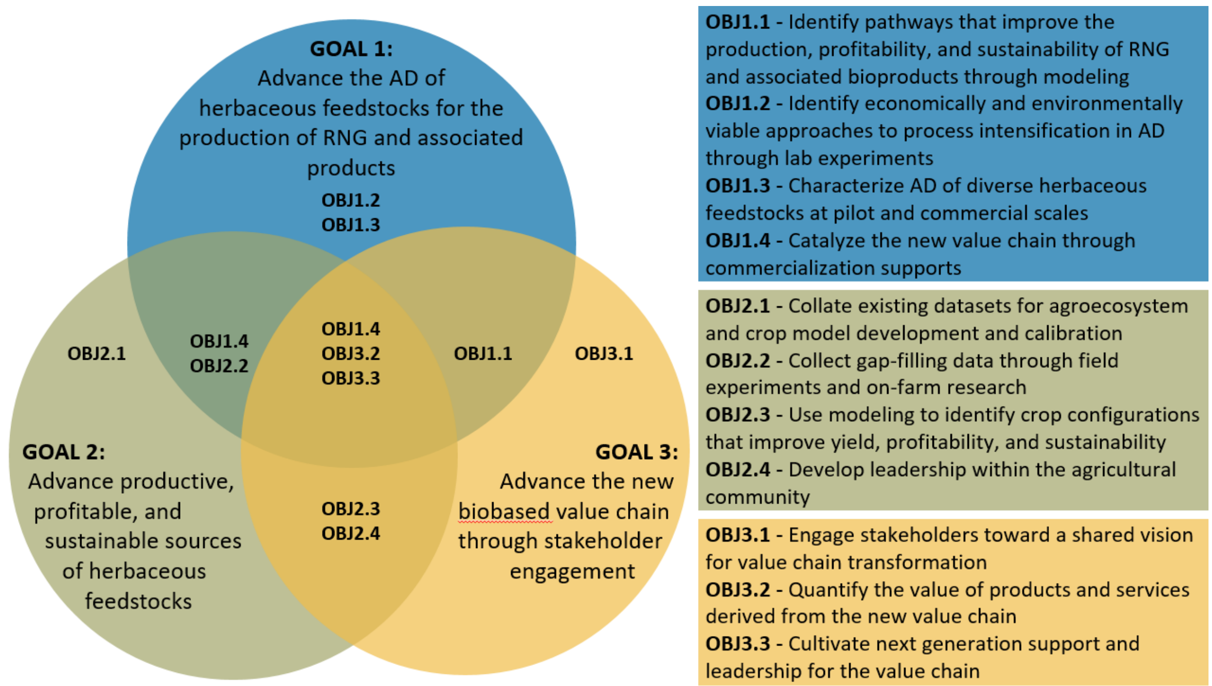

Figure 2. Integration among C-CHANGE goals and objectives.

Background

The need for a C-CHANGE: Agricultural systems in the Upper Midwest and Mid-Atlantic regions are highly productive and well-constructed for past conditions. While supporting state and national economies, these systems no longer adequately sustain farmers, rural communities, land, or water resources. For example, today's dominant agricultural systems require few farmers,[4] are dependent on economic subsidies,[5] and can have negative impacts on rural communities.[6,7] Soil loss and degradation associated with dominant annual cropping systems have been widespread and prolonged, and may undermine the nation's ability to sustain long-term, efficient production.[8,9] Conventional livestock manure management practices challenge air quality, water quality, and public health.[10–12] Water quality impairment associated with agriculture impacts individuals, communities, and ecosystems,[13–15] including downstream in the Chesapeake Bay[16] and the Gulf of Mexico[17]. Farm habitats, crucial for sustaining wildlife populations, are depauperate.[18–20]

While antecedents for more sustainable systems exist, supporting concepts, technologies, infrastructure, and markets are currently immature and not well integrated. Many paradigm-changing farm, business, industry, and educational practices are thus rendered non-competitive. For example, despite its potentially positive impacts, the development of cellulosic ethanol, widely expected to monetize perennial and winter crops, energize rural economies, improve soil and water quality, and enhance biodiversity, has stagnated.[21] In 2007, Congress called for cellulosic biofuels to scale up to 4.5 billion gal yr^{-1} by 2016, but only 0.16 billion gal were produced that year.

Of that 0.16 billion gal, over 98% was biogas upgraded to RNG.[21,22] By leveraging RNG's advantage, this project will identify and remove barriers that inhibit its growth, while boosting the viability of emerging concepts, technologies, infrastructure, and markets to enable transitions to a more sustainable agricultural system through coordinated research, education, and extension.

State of the Art: While basic forms of AD have existed for centuries, changing conditions have dramatically improved the value of this technology to US agriculture.[23,24] The scalability (from individual farms to clusters of farms) of the core technology already allows flexibility in terms of coproduct processing, financial models, and supply chain relationships.[25,26] Improving its flexibility with respect to herbaceous feedstocks will encourage the forms of crop diversification needed to meet farm financial and ecosystem service goals.[27] Following the US Environmental Protection Agency's approval of RNG from AD to satisfy Renewable Fuel Standard targets, the value of AD's primary product – methane (CH_4) – increased by an order of magnitude.[28] Longer term, the US is rapidly evolving its energy, chemicals, and materials industries to use methane as the fundamental process molecule, offering a pathway to biobased products that leverages massive nationwide investments in natural gas infrastructure and process technology. By using existing natural gas storage and the natural gas turbines, RNG can leverage that infrastructure to provide *dispatchable* renewable electricity.[29] This is a crucial advantage of RNG over solar and wind technologies, which depend on expensive batteries (\$0.30 to \$0.60 kWh^{-1}) for energy storage; RNG adds flexibility, reliability, and resilience to the overall renewable energy sector.[30,31] Further, the option to produce high-value products once these technologies are commercially mature offers access to highly lucrative markets without government incentives.[32–36] Co-products from AD (digestate, biochar) could help farmers cut input costs, build soil health, and reduce vulnerability to extreme weather events.[37,38] Coupling digestion of herbaceous biomass and manure – as we propose here – will allow mid-sized farms to achieve economies of scale and the resultant profitability currently only available to the largest livestock operations. It will also provide additional benefits important to farmers (i.e., additional markets, crop flexibility, soil health, nutrient retention) and society (e.g., reduced odor, reduced pathogen transport, water quality, wildlife and pollinator habitat).[12,39–43]

Current Limitations/Gaps in Knowledge: AD that couples manure with much larger quantities of herbaceous biomass (i.e., co-digestion[44]) is essential to advancing the proposed biobased value chain. Yet, RNG markets are novel in the US[45] and are thus limited by the uncertainties and inefficiencies of an emerging technology.[46,47] Additional research is needed to address pretreatment and co-treatment technologies;[21,48–50] co-digestion of recalcitrant biomass at high solids concentrations;[51,52] process stabilization, intensification, modularization and automation;[36,53] process integration with gas cleanup and upgrading;[24,54] digestate valorization;[35] social, behavioral, and economic barriers;[55,56] and the value to be returned to farms,[35,43] including the value of associated ecosystem services.[57,58] Significant innovation and transformation are needed within existing crop and livestock systems to bring this system to scale, including the sourcing of sustainable feedstocks.[59,60] A substantial, integrated effort is crucial to develop necessary technical knowledge and infrastructural supports, such as best practices, decision tools, trainings, and workforce development.

The Team: C-CHANGE is uniquely positioned to provide the needed scientific breakthroughs, technological support, and demonstrations to develop this new biobased value chain. The transdisciplinary partnership is led by Iowa State University (ISU) and Penn State University (PSU) – land-grant institutions and distinguished leaders in agricultural bioeconomy – and Roeslein Alternative Energy (RAE), an award-winning biofuel engineering company that joined with Smithfield Foods in 2014 to develop one of the largest AD projects in US history.[61] These lead institutions are supported by FDC Enterprises and the USDA Agricultural Research Service's National Lab for Agriculture and the Environment. FDC Enterprises has provided on-the-ground logistical support for biobased projects for over a decade, and has established and managed over 335,000 acres of native warm-season grasses across 26 different states. Partners include 10 farms, 10 private enterprises, 4 trade organizations, 3 state/ federal organizations, and 13 non-governmental organizations (see DOCUMENTATION OF COLLABORATION). With the advisory board, more than 55 organizations have already helped to refine the scope and priorities of C-CHANGE and have enlisted for demonstrations, deployment, and regional scale -up (Fig. 3).

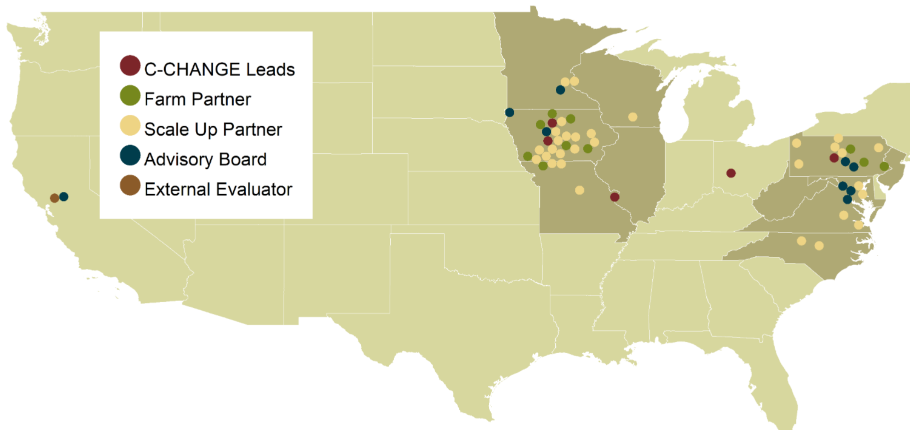

Figure 3. Location of C-CHANGE focal regions (dark tan), leads, and partners. An additional advisory board member is located in Italy.

Previous Activities and Preliminary Data

We have also developed substantial resources and capacity to meet project goals and objectives, including the development of stakeholder networks (Fig. 3), datasets and tools (Table 1), and other infrastructure (see EQUIPMENT and FACITLITES AND OTHER RESOURCES). Our proposed work has been informed by decades of lab and field research and comprehensive stakeholder input in the form of four surveys, hundreds of personal meetings, and dozens of workshops. Specific input from thousands of farmers has been obtained, analyzed, and integrated in the goals and objectives of the proposed work. Stakeholder data covering farmers, farmland owners, and relevant agricultural groups have been collected through several previous research projects. These include: the Iowa Farm and Rural Life Poll (IFRLP), an annual panel survey of Iowa farmers conducted since 1982, which regularly measures farmers' perspectives on crop production and nutrient, soil, and water management;[62] the Iowa Nutrient Reduction Strategy survey, a 5-year (2015-2019) annual farmer survey focused on nutrient loss reduction practices;[63] the 2012 Corn Belt-wide survey of farmers measuring attitudes toward biomass production for energy conducted by the NIFA-funded CSCAP and U2U projects;[64] in-depth interviews with 159 farmers on barriers to and facilitators for use of cover crops, diverse rotations, and perennials through the NIFA-funded CSCAP;[65] a 2006 survey measuring Iowa farmer willingness to supply corn stover as biofuels feedstock;[66] in-depth interviews and stakeholder workshops on the strategic integration of perennials and the co-management of agricultural landscapes in Iowa;[67–70] and in-depth interviews with Pennsylvania scientists, educators, and state agency representatives focused on the development/diffusion of perennial switchgrass, miscanthus, and willow; willingness to plant biomass crops, and support for biobased industry development.[71–73] C-CHANGE further integrates numerous existing models and experiments to answer critical research questions, improve decision making, and foster learning. We are leveraging significant previous USDA NIFA funding in the process (Table 1).

Table 1. Summary of models/experiments already established, employed by C-CHANGE team. FACILITIES AND OTHER RESOURCES includes details of these and other team resources.

Name	Description	Funding by
GOAL 1 Model: IBAM	IBAM, the Iowa Biogas Assessment Model, combines information on biomass availability with AD economic and environmental impact process models[74–76]	Iowa Energy Center, Iowa Economic Development Authority
GOAL 2 Model: Foresite with APSIM	Foresite is an economic assessment tool and collection of public data sources[77–79] that is being integrated with APSIM, the Agricultural Production Systems sIMulator, a process-based agricultural model[80–83]	USDA-NIFA, NSF, ISU, Iowa Nutrient Research Center
GOAL 2 Model: Cycles	A process-based, multi-year, multi-crop, and multi-soil layer simulation model[84–86]	USDA-NIFA, EPA, NSF, US DoD, US DoE
GOAL 2 Experiment: IA - COBS	Provides quantitative, side-by-side comparison of five annual and perennial biofuel cropping systems[87–90]	Conoco-Philips, ISU, Iowa Nutrient Research Center, Leopold Center, USDA – NASA Carbon Cycle Science Program
GOAL 2 Experiment: PA – DCS (Dairy Cropping Systems)	Includes three 6-year, no-till dairy crop rotations and a corn-soybean rotation[91–98]	USDA-SARE, PSU, LTAR-ARS USDA
GOAL 2 Experiment: MO - Ruckman Farm	3 biomass cropping systems with swine manure application; replicated 6 times on 1.5-17.8 ac fields	USFWS, ISU, and in-kind by RAE and Smithfield Foods

B. RATIONALE AND SIGNIFICANCE

Rationale for the Proposed Project

The dominant regional agricultural systems at present do not utilize resources efficiently and require substantial external inputs in the form of nutrients, energy, and financial capital, often as government subsidies.[99,100] The use of assets underpinning these agricultural systems – including land, equipment, and labor assets – is particularly inefficient when land is left fallow for 4–7 months of the year,[101,102] or when dominant annual crops are planted to areas where they do not perform well.[77,103,104] Tighter coupling between production and processing of biomass by siting AD technology on farms, at livestock facilities, or ethanol plants would take advantage of existing infrastructure while also improving the efficiency and sustainability of resource use. It would also increase the number of farm products for more diverse and stable cash flows.[59,105] Co-digestion of sustainably sourced herbaceous feedstocks with manure has the potential to produce resilient, marketable energy products (RNG, electricity, and process heat), bioproducts from digestate (compost, biochar, and activated carbon;[106] and biobased chemicals (carboxylic and hydroxycinnamic acids that can be turned into plastics, latex paint, food preservatives, flavoring additives, sunscreens, cosmetics, acrylic acids, fragrances, and styrene)[107]. The inputs (perennial and winter crops, and annual crop residues) and outputs (digestate, compost, biochar)[37] are compatible with but produce substantially greater levels of ecosystem services than achievable through current agricultural systems.

In contrast to other biobased strategies, two major market drivers make this the ideal time to scale-up agricultural AD to meet national bioeconomy goals. The first is the Federal Renewable Fuel Standard (RFS2) price premium for RNG. Without incentives, methane derived from biogas was sold as compressed RNG for a modest premium of \$4.93 GJ^{-1}.[108,109] In 2014, the EPA designated RNG from cellulosic sources (including landfills and manure) eligible for RFS2 D3 (cellulosic) Renewable Identification Numbers (RINs) that in 2019 are worth an additional \$5.20–\$17.60 GJ^{-1} (\$0.64–\$2.16 per gallons gasoline equivalent, or gge).[110] Three RNG projects by our commercial partner RAE are currently in operation,[45] and half of the 34 digesters currently under construction are targeting the D3 RINs market, including an additional seven by RAE.[45] *C-CHANGE will foster expansion by developing and demonstrating a suite of integrated AD feedstocks, technologies and markets to expand digester profitability to the over 8,000 mid-sized swine and dairy farms*[45] *and beyond to farms that do not have livestock.* The second market driver is farm profitability. Yield monitoring and economic modeling indicates over 20% of the cropland devoted to annual species like corn loses money as a result of poor soil, flooding, or drought.[103,111] Strategically integrating herbaceous biomass crops as winter crops or onto areas where annual crops are underperforming will increase field and farm profitability, and also improve nutrient retention and water quality[77,112], reduce soil loss[113,114], and enhance habitat for wildlife and pollinators[115,116].

Relationship with USDA NIFA Program Area Priorities

C-CHANGE addresses the USDA NIFA Sustainable Agricultural Systems Program's goal of fostering economic development and prosperity in rural America by catalyzing the bioeconomy through value-added innovation, and production of high-value biobased chemicals and other products built from agricultural feedstocks. C-CHANGE will substantially contribute to this goal by constructing and demonstrating a new value chain that combines: (1) full-year crop production through the temporal and spatial integration of winter and/or perennial crops using state-of-the-art precision agricultural technology; (2) the expansion of agricultural markets through AD of sustainably sourced herbaceous biomass with manure; and (3) significant support for social, infrastructure, and market innovations. The specific trajectory we envision for meeting USDA's goals starts with existing swine and dairy manure systems. The US EPA estimates that AD is currently cost-effective for swine operations with more than 2,000 heads and dairies with more than 500 cows,[43] with a total biogas potential of 171 mmBTU yr^{-1}, or 1.5 billion gge yr^{-1}. Incorporating a winter crop onto the 96 million ac of winter fallow currently available across the US Corn Belt would result in at least 123 million dry tons of additional biomass,[117] which we estimate can produce 9.4 billion gge yr^{-1} of RNG. Food waste, which is currently co-digested in about 15% of farm digesters because of profitable tipping fees, has a fresh weight estimated at 1.5 billion gge yr^{-1} of RNG.[118] With these high-protein feedstocks providing process stability[52,119] and adding value to coproducts,[120] AD systems can add perennial crops to achieve economies of scale, even for farms without livestock or with limited acres in annual crops. Nationwide, the DOE estimates that at least 411 million tons of herbaceous energy crops (not including winter crops) and 176 million tons of crop residues (with removal rates in line with soil health) would be available at a price of \$60 Mg^{-1} by 2040.[121] Assuming a 60% energy yield of biomass to RNG, these energy crops and residues could produce another 31.4 billion gge $yr^{-1}$and 13.4 billion gge yr^{-1}, respectively. The total output of RNG could be 57.2 billion gge yr^{-1} (Table

2), the economic impact of which would be transformational. For example, our preliminary estimate, based on Liu and Iutzi[122], is that an expansion of just the current cover crop supply chain into winter crops on these 96 million ac would result in as many as 14,000 additional jobs and \$1.9 billion in total output. These winter crops converted through AD would sell for more than \$43 mmBTU^{-1}, resulting in revenues of *\$46.4 billion* yr^{-1} under the market created by California's Low Carbon Fuel Standard. *The total RNG indicated in Table 2 would be worth \$85.2 billion annually based on an average 2019 RFS2 D3 RIN price of \$1.50* gge^{-1}. For fuels sold in the California market, incentives are even higher: with Low Carbon Fuel Standard prices currently at \$45.37 GJ^{-1} (\$5.50 gge^{-1}). An additional \$6.54 GJ^{-1} (\$0.80 gge^{-1}) could be garnered if the CO_2 byproduct of biogas to RNG separation went to geologic carbon storage. The resulting digestate could be directly land-applied as an amendment to improve soils, while upcycling just 15% would produce 57 billion pounds of biochar per year to holistically meet USDA NIFA goals for productivity, profitability, and sustainability.

Table 2. Expected 2043 annual renewable natural gas (RNG) production through C-CHANGE.

Feedstock Source	Billion mmBTU^{-1}	Billion GJ^{-1}	Billion gge^{-1}
Livestock manures	0.17	0.18	1.49
Food waste	0.18	0.19	1.52
Winter crops	1.08	1.14	9.38
Energy crops	3.60	3.80	31.35
Agricultural residues	1.54	1.63	13.43
Total	**6.58**	**6.96**	**57.18**

Significance of Agricultural Systems Investigated by C-CHANGE

Our project will focus on agricultural systems in Iowa, Missouri, and Pennsylvania, which contribute significantly to the economic value created by agricultural systems and rural economies in the US. In Iowa, 30.6 million ac of farmland support 86,000 farm operations.[123] Iowa agriculture sold \$29 billion products in 2017, second to California. Iowa ranks first in the nation in corn, swine, ethanol, and feed grain exports. Iowa's dairy industry is smaller than other states but still impactful.[123] Yet, Iowa faces significant new challenges to delivering abundant, affordable, and safe food to a growing human population.[8,14,124–128] It was ranked by the US EPA in 2018 as having the highest market opportunity of any state for biogas development.[43] Agricultural production in northern Missouri is similar to Iowa for crops, which are primarily fed to livestock. The value of agricultural products sold in 2017 was \$10.5 billion. Missouri has 95,000 farm operations working 28 million ac.[129] While beef cattle and broilers represent much of the state's livestock resource, hog production is concentrated on large farms of 40,000 to 170,000 hogs in northern counties.[61] The concentration of manure resources associated with these large farms causes social-ecological challenges and made the region a logical starting point for RAE and Smithfield Foods to bring AD technology to the state.[61] In Pennsylvania, 7.3 million acres of farmland support 53,000 farm operations,[130] which sold \$7.8 billion in agricultural products in 2017. Pennsylvania is more diverse than Iowa or northern Missouri for commodities and crops produced. Long a dairy state, Pennsylvania ranked sixth nationally in milk sales and eighth for poultry and eggs in 2017. Recent low milk prices, increasing production costs, and falling consumer demand challenge traditional expectations for dairy farm viability. All three states have persistent water quality concerns associated with their current forms of agriculture, with downstream impacts to the Mississippi River/Gulf of Mexico (IA, MO)[131] or Chesapeake Bay (PA).[132]

C. APPROACH

GOAL 1 – Advance the AD of herbaceous feedstocks for the production of RNG and associated products (Lead: Richard)

For over 50 years, AD has been used to treat manures, crop residues, and a wide range of municipal and industrial organic wastes.[133] Its ability to dramatically reduce odors and pathogens, convert organic nitrogen to more available and predictable ammonia for fertilization, and generate renewable energy is well documented.[12,58,59,134] However, adoption in the US has been slow because of inadequate economies of scale, sensitivity of the anaerobic microbiome to process variability, and high levels of required technical expertise.[24,43,55] C-CHANGE will address these issues through research to improve economic prospects associated with increasing feedstock diversity, including herbaceous biomass; increase diversity of markets by expanding products to include biobased chemicals and valorizing co-products of AD; improve operational resiliency by incorporating process intensification/innovation in AD systems; and replace economies of scale with economies of number by introducing modular manufacturing and automation.

OBJ 1.1. Identify pathways that improve the production, profitability, and sustainability of RNG and associated bioproducts through modeling (Mba Wright, Costello, Bansal, Brown, Richard)

Rationale: The overall economic and environmental performance of an AD system depends on many factors. AD has not been optimized for reactor configuration or coproducts, particularly for the herbaceous biomass-dominated systems needed to achieve the goals shown in Table 2.[51,119] Conventional biosolids and slurry manure reactor designs are not adept at conversion of herbaceous biomass.[135] Several reactor configurations have been shown to improve processing; i.e., solid state[136] or leached bed reactors,[137] stirred reactors with solids recycle,[138] thermophilic[139] or temperature-phased reactors,[140] pretreatment,[48,141] and co-treatment.[142] While these strategies have been shown to intensify conversion via both smaller reactor size, reduced residence times, increased RNG yield, and improved process stability, comparative technical and economic analyses are lacking. While some prior research exists on decision-making models for biofuel supply chains, it only represents monetary values of cash flows.[143,144] Multi-dimensional non-monetary objectives such as social and environmental factors are also strong motivators for various value chain actors.[145,146] Identification of viable pathways requires systems analysis to support experimental/demonstration and commercialization decisions.

Question: What scales and combinations of feedstock/pretreatment/digestion/products, coupled with truck and pipeline transport to large-scale, high value markets, provide the lowest risk and greatest economic returns for small- to medium-size farms?

Methods/Work Plan: Process models, technoeconomic analyses (TEA), life cycle assessment (LCA), and pro forma cash flow modeling will be developed for diverse scenarios of anaerobic digestion. TEA and LCA analysis will be performed with Aspen Plus for process design, SimaPro and GREET.net for estimating environmental impacts, and IBAM for biomass supply and logistics. Pro forma supply chain models will be built in MS Excel. Specific tasks are as follows. <u>Task 1.1.1.</u> Enhance the IBAM model to screen through combinations of feedstock, conversion, and product portfolio to identify the herbaceous biomass-dominated systems needed to achieve economies of scale on small- to mid-sized farms and to recommend to Goal 2 modeling efforts. <u>Task 1.1.2.</u> Conduct meta-analysis of existing data on systems for AD of manure and plant material, including process stability boundaries and tipping points. <u>Task 1.1.3.</u> Conduct market analysis on value of potential RNG and associated bioproducts with and without incentives. <u>Task 1.1.4.</u> Evaluate supply chain logistics and optimal facility scale options for feedstocks and products according to Net Present Value (NPV), pollution emissions, and greenhouse gas (GHG) emissions. <u>Task 1.1.5.</u> Select up to 7 scenarios of feedstock supply/feedstock logistics/conversion pathway and scale/products/markets for a TEA/LCA risk-based analysis based on sensitivity and uncertainty analyses on model outputs and stakeholder input. These results will be used to recalibrate research investments in Y2 – 5 and to down-select for the following 3 tasks. Task 1.1.6. Conduct TEA on selected AD enterprises to estimate NPV and economic uncertainty. Task 1.1.7. Conduct LCA on selected AD enterprises to estimate pollutant and GHG emissions and their uncertainty. Task 1.1.8. Develop mathematical representations of value chain preference attributes for industrial partners in Y2. Task 1.1.9. Develop a pro forma model to represent cash flows and performance scores on non-monetary preferences for all value chain actors in Y3 for specific scenarios such as specific land use allocations and digester capacity. Task 1.1.10. Conduct 6 controlled focus groups with approximately 5 farm owners, supply chain and service businesses, and industrial market partners to understand if risk-sharing tools result in greater willingness of value chain actors to participate in RNG and associated bioproduct value chains in Y4. Task 1.1.11. Integrate methods into a farm- to national-scale AD systems analysis to determine market adoption potential, potential returns, environmental impacts, and risk factors.

Outputs: Assessments of technical, environmental, economic risks of promising AD enterprises.

Outcomes: Farmers, entrepreneurs, and other potential investors will have information on economic and environmental performance of enterprises based on AD of herbaceous feedstock and manure mixes well suited to agriculture in the Midwest and Northeastern US.

Limitations: Large uncertainties are common for data used in TEA/LCA, leading to large uncertainties in results. OBJ 1.2, 2.1, and 2.3 research will be designed to reduce these uncertainties.

OBJ 1.2. Identify economically and environmentally viable approaches to AD process intensification through lab experiments (Richard, Brown, Ciolcosz, Trabue, Wen)

Rationale: The outputs of OBJ 1.1 will inform our selection of AD scenarios for further development through experimental investigations in Y2 – 5. Based on current understanding of the field, examples of studies likely to be undertaken in OBJ 1.2 include the following. Co-treatment (milling during fermentation) and thermophilic (55 °C) fermentation of switchgrass have shown a 2-fold increase in solubility[142] and a 6-fold reduction in residence time,[139] respectively. Pretreatment with alkali not only improves the digestibility of lignocellulosic biomass through partial delignification, but creates hydroxycinnamic acids, potentially high value co-products from the AD system.[107] Solid digestate, representing up to 30 wt% of the products from AD, is an attractive co-product for valorization, except that it is wet and contains substantial amounts of lignin, a very difficult material to convert to useful products. However, a combination of composting[147] to reduce moisture and autothermal pyrolysis[148] to depolymerize the lignin content without external sources of thermal energy can produce pyrolysis oil, which can be upgraded into fuels and bio-asphalt, and nutrient-rich biochar, which is attractive as soil amendment and carbon sequestration agent that is more readily transported than raw or composted digestate.[37] The oxidative environment of autothermal pyrolysis dramatically increases the porosity of biochar, with specific surface areas (BET-N2) of 445 m^2 g^{-1}, expanding its potential markets to include activated carbon. Adding biochar to digesters also has potential to improve digestion rate and methane yield as a result of pH buffering and contaminant adsorption[149] and promoting direct interspecies electron transfer,[150] as has been demonstrated for activated carbon. Each of these process configuration strategies will be stress-tested for resilience relative to changes in feedstock, temperature, pH, and other factors (alkali pretreatment, co-treatment milling intensity, biochar supplementation) as appropriate to understand process stability, recovery rates, and tipping points toward process failure. This information will inform process automation and adaptive management strategies as well as data acquisition and control hardware and software configurations.

Questions: Can process intensification, integration, and automation of biomass pretreatments/co-treatments, reactor configurations, biochar additions, energy integration, and co-product valorization strategies greatly decrease risk and improve resilience of farm digester enterprises?

Methods/Work Plan: AD experiments will use fresh, ensiled, or pretreated herbaceous biomass mixed at high ratios with ensiled winter crops and/or swine or dairy manure. Trials will be conducted at both ISU and PSU laboratory-scale digesters with pH and temperature control to study temperature-phased, leached bed, and co-treatment configurations. Biogas yield will be continuously measured and the headspace will be periodically sampled for H_2S, NH_3, CH_4 and CO_2. Slurry samples will be removed periodically and analyzed for moisture, pH, organic acids, and solubilization using quantitative saccharification. Task 1.2.1. Evaluate alternative strategies for digester thermal management. Investigate direct combustion of dry biomass, RNG, or fossil natural gas; and digestate valorization using composting for bio-drying before final drying and autothermal pyrolysis converting dried digestate residues to phenolic oil, biochar, and waste heat suitable for heating of digesters. Task 1.2.2. Evaluate impact of alkali pretreatment of biomass on methane production potential and kinetics. Demonstrate recovery and valorization of hydroxycinnamic acids. Task 1.2.3. Evaluate impact of milling during fermentation (co-treatment) on RNG production potential and kinetics. Task 1.2.4. Evaluate impact of biochar incorporation during AD on RNG production potential and kinetics. Task 1.2.5. Evaluate process stability and determine critical process parameters to provide guidance for full-scale biomass digesters.

Outputs: Improved data on (1) feedstock utilization, digestion rates, and RNG yields for AD of mixtures of herbaceous feedstocks and manure using various pretreatments/co-treatments and reactor configurations; (2) moisture removal levels and rates in solid digest composting; and (3) yields of pyrolysis oil and biochar under different digestate compositions and moisture content.

Outcomes: Improved TEA and LCA of AD systems that incorporate innovations such as pretreatment/co-treatment and solid digestate valorization.

Limitations: Many potential pretreatment options and digester configurations exist. Experimental factors selected for analysis will be based on OBJ 1.1 results. Biological systems have high variability which may prove challenging for some processing intensification and automation strategies, which we will address through close coupling of OBJ 1.2 and 1.3. Although autothermal operation enables pyrolysis of wet feedstocks, the moisture content of digestate, even after mechanical dewatering, may require some drying prior to pyrolysis, either through thermal drying from burning exhaust gas from the pyrolyzer or partial composting.

OBJ 1.3 Characterize AD of diverse herbaceous feedstocks at pilot and commercial scales (Richard, Brown, Ciolkosz, Costello, Hristov, Karsten, Roeslein, Toraman, Trabue, Wen)

Rationale: Model and lab results rarely translate precisely to pilot or commercial operations, especially with solid feedstocks.[151] We will conduct pilot experiments of process innovation and control strategies recommended by OBJ1.1 and 1.2 results using existing 80 L anaerobic digestors at PSU. Experimental results will inform operations of RAE's commercial facilities in northern Missouri; tests at that scale will provide further knowledge refinement.

Questions: Do the strategies recommended by OBJ 1.1, 1.2, and 2.1 improve the rate, yield, and profitability of biogas and associated bioproducts at pilot and commercial scales? How can the multiple products of AD be optimized for system performance and profitability?

Methods/Work Plan: Results from lab experiments will be tested at pilot scale at PSU and inform commercial operations of an AD plant at RAE's Missouri facility. Biogas production rate and composition will be measured by flow meter totalizers and gas analyzers and used in process control algorithms. Biogas production rate/composition will be measured by flow meter totalizers and gas analyzers. Task 1.3.1. Refine selection of feedstock and pretreatments based on outcomes of OBJ 1.1-1.2 and 2.1 investigations. Task 1.3.2. Specify pilot-scale testing protocol for up to 5 experiments. Task 1.3.3. Conduct pilot-scale commissioning, startup, and experimental trials to document performance with herbaceous feedstocks. Task 1.3.4. Demonstrate pilot-scale feasibility for upgrading methane for production of fuels and chemicals. Task 1.3.5. Use results to design and conduct further commercial scale testing. Task 1.3.5. Conduct commercial tests and analyze results.

Outputs: Novel methods that improve the production, profitability, and sustainability of RNG and associated bioproducts from mixed herbaceous biomass and manure feedstocks.

Outcomes: Demonstrating innovations in AD at meaningful scale and for year-round operation will provide the technical data farmers, entrepreneurs, and other investors need to make technology investment decisions.

Limitations: Traditional feedstock supply for biorefineries requires coordination with harvest/storage activities, which can occur in as little as 4-6 weeks once per year. The AD system and feedstock mixes investigated overcome this traditional limitation as animal waste is continuously generated, and winter/double crops add a 2-3 mo harvest window to warm weather months.

OBJ 1.4 – Catalyze the new value chain through commercialization supports (Ciolkosz, Brown, Comito, Richard, Roeslein)

Rationale: Market-based approaches to behavioral change have the greatest potential to be sustainable in the long-term. However, the marketplace is competitive and many businesses fail from lack of basic knowledge and decision guidance. Entrepreneurs seeking to grow/profit from the RNG and associated bioproducts value chain require commercialization support to enable successful business ventures.[91,152] The C-CHANGE team will support the development and expansion of industries by creating connections, courses, case studies, and webinars, and providing one-on-one guidance.

Methods/Work Plan: Task 1.4.1. Organize and deliver annual Digester Day in Y1-Y5 at the PSU digester/student farm/bioenergy crops site. Content will include principles of operation, equipment, project development and economics, market development, and financing. 1.4.2. Organize and deliver a webinar each year Y1-Y5 on developing project knowledge. Each webinar will feature a different Goal 1 researcher. Task 1.4.3. In Y2, deliver a Biomass and Biogas short course to attract and educate entrepreneurs, project developers, and related stakeholders, providing key education on the value chain. Knowledge developed through OBJ 1.1 – 1.3 will guide course development. Follow-up interactions with stakeholders will provide guidance and support as needed. Task 1.4.4. Create detailed business case studies in Y3 that provide strategic, tactical, and operational guidance on value chain design, operation, and economics. Prepare three case studies based on the dairy, swine, and poultry sectors. Task 1.4.5. Carry out a market analysis of farm-sourced biogas-derived products in Y3, and prepare a report that details likely markets and pathways to commercialization for dissemination through extension publications, courses, webinars, and field days. Task 1.4.6. Organize and deliver a commercialization short course in Y4-Y5 to spur new businesses and transfer C-CHANGE research findings and recommendations. Short course content will be integrated into PSU's online Applied Biogas Technology course.

Outputs: 5 field days, 5 webinars, 2 short courses, 3 business case studies, 3 market analyses, 1 updated online course.

Outcomes: Strategic, tactical, and operational guidance on the design, operation, and economics of the biobased value chain for entrepreneurs and businesses involved in rural economic development and sustainability.

Limitations: As with any new industrial sector, the bioeconomy in general and bioproducts in particular suffer from uncertainty and risk. We have assembled a comprehensive program to address several major risk factors through diversity, resilience, and information technology strategies. Policy risk including government subsidies for RNG are a particular concern.

GOAL 2 – Advance productive, profitable, and sustainable sources of herbaceous feedstocks (Lead: Liebman)

We will provide Goals 1 and 3 with iterative estimates of biomass from winter crop, pasture, prairie, and annual crop residues (for both target AD herbaceous feedstocks and current dominant crops) through coupled modeling, field experimentation, and on-farm research and demonstration. Members of our team have been conducting long-term field experiments on perennial, winter, and annual crop systems and incorporated findings into agroecosystem models to determine agronomic, economic, and environmental performance under a broader set of conditions.
[77,91,153,154] Here, we will collate datasets from Iowa and Pennsylvania and use them to train, test, employ, and compare two leading agroecosystem models for our regions: APSIM and Cycles (Table 1). Field and subfield level simulation model outputs will feed into Foresite, a computational framework we developed to predict economic and environmental impacts of cropping systems at a subfield scale.[77,78] Subfield management provides the opportunity to spatially integrate perennial herbaceous feedstocks within annual crop fields to meet financial and ecosystem service goals.[77,101,155]

OBJ 2.1. Collate existing datasets for agroecosystem and crop model development and calibration (Liebman, Kemanian, Helmers, Karsten, Thompson, VanLoocke, Heaton)

Rationale: The high levels of uncertainty and/or low confidence in estimates of biomass cropping systems' performance for AD feedstock production will be addressed by focused empirical data collection to improve predictions of value chain productivity, profitability, and sustainability.[156] We have 20 collective site-years of AD biomass feedstocks data in hand to support model-ing and provide decision support data for demonstration in Y1.

Question: What data gaps limit prediction of supporting (e.g., soil health), provisioning (e.g., yield), and regulating (e.g., nutrient, water cycling) ecosystem services and profit delivered by herbaceous AD feedstocks?

Methods/Work Plan: We will assimilate data from diverse projects into one shared repository of quality-assured data for model training and testing. Task 2.1.1. Published and unpublished data on crop biomass, rooting depth, soil aggregation, texture, carbon and nutrient status, water runoff and drainage, dissolved nutrients, GHG emissions, and on-site weather data from all years of the COBS and PA-DCS projects (Table 1). Task 2.1.2. Develop a shared data repository (similar to the one used in the CSCAP[157]), where newly collated extant data, new measurements (OBJ 2.2), and data produced through modeling (OBJ 2.3) will be housed.

Outputs: An organized, annotated, citable, shared data repository.

Outcomes: Foundation for automated and iterative model calibration, testing, comparison, and uncertainty assessment. Documented assessment of knowledge and data gaps.

Limitations: By using data from both ISU and PSU sites and two agroecosystem models, we will be able to partition uncertainty between field sites and model configurations.

OBJ 2.2. Collect gap-filling data through field experiments and on-farm research

(Liebman, Karsten, Helmers, Schwartz, Thompson, Heaton)

Rationale: Critical data gaps remain that limit our ability to predict biomass feedstock performance: additional detail is needed on (1) perennial and winter crop phenology,[88,158] (2) AD digestate substitution for manure, and (3) AD digestate management to reduce nutrient loss. We will measure system inputs (e.g., micrometeorological conditions, fertilizer, fuel use) and outputs (e.g., yield, crop development dynamics, drainage, dissolved nutrients, soil health, profit) at our heavily instrumented COBS and PA-DCS research sites (Table 1). Data collection on research farms will be augmented with targeted data collection on partnering commercial farms (Fig. 3; see DOCUMENTATION OF COLLABORATION). By using data from both research and commercial farms, we will acquire high-resolution biophysical and geochemical data to fill gaps.

Questions: How does addition of a winter crop change soil health, water and nutrient cycling, and profit of annual crop systems? How do perennial feedstocks compare? How does digestate compare to manure as a fertilizer? What drives observed differences, e.g., feedstock/manure/digestate composition, weather, crop management, soil type?

Methods/Work Plan: <u>Task 2.2.1</u> Acquire energy, water, and nutrient flow data at high temporal and spatial resolutions using in-place weather stations, monitored drainage, yield monitors, and analytical facilities. Fill gaps in extant data, e.g., rooting depth, soil aggregation, and phenology of perennial and winter crops. <u>Task 2.2.2</u> Assess management of perennial, winter, and annual crops at partnering commercial farms (Fig. 3), including the Smithfield Foods-RAE Ruckman on-farm research site (Table 1). <u>Task 2.2.3.</u> Assess liquid digestate injection, cover crop interseeding, and application to established perennials at up to two commercial farm sites, to be determined based on initial data collection. Collect yield, weather, and management data.

Outputs: 60 datasets (one per year for 2 research and 10 commercial sites) detailing system inputs and outputs needed for modeling; Y2-Y5 annual reports to10 farmer cooperators (40 total).

Outcomes: Long-term (>15 yr) knowledge of the productivity, profitability, and sustainability of biomass cropping systems. Translation of experimental research results to commercial farms.

Limitations: All models are constrained by the accuracy of their inputs, parameterization, and assumptions. We compare two process-based models trained with multiple streams of stakeholder data to identify where predictions are limited by data versus model attributes.

OBJ 2.3. Use modeling to identify crop configurations that improve biomass yield, profitability, and sustainability (VanLoocke, Kemanian)

Though perennial and winter crops appear to be economically and environmentally sustainable AD feedstocks,[59,100] these crops are not yet widely adopted in our target regions, and thus their expected performance must be modeled rather than being directly measured. We will simulate herbaceous feedstock as inputs to OBJ 1.1 value-chain scenarios, using the process-based agroecosystem models APSIM and Cycles (Table 1). We will combine public data on land use, soils, and economics in the Foresite spatially explicit computational framework (Table 1). Foresite links economic costs and returns of crop production with process-based model simulations (output from APSIM and Cycles) net primary productivity, yield, hydrology, GHG emissions, soil carbon, and nutrient retention. The addition of process-based modeling to the framework proposed here is **major innovative step**. These models allow consideration of outcome cascades resulting from changes in location or management[77] and quickly and cost-effectively identify best management practices, benefits, and gaps in the production chain, thus merging biophysical and human dimensions.

Questions: What is the optimal configuration of perennial, winter, and annual crops for a given

AD scenario? How does AD digestate effect farm agronomic, economic, and environmental performance compared to manure or inorganic fertilizer?

Methods/Work Plan: Task 2.3.1. Develop, train, and test APSIM and Cycles modules for prairie, pasture, and winter crops using data from OBJ 2.1 and OBJ 2.2. Task 2.3.2. Simulate AD scenarios developed with Goals 1 and 3 at a range of spatial (subfield, farm, state, regional) and temporal (daily to decadal) scales, including on partnering commercial farms. Task 2.3.3. Compare APSIM and Cycles predictions of provisioning and regulating services in shared scenario testing for inter-model comparison and uncertainty assessment. Task 2.3.4. Feed APSIM and Cycles output into Foresite profitability framework to calculate economic and environmental performance of AD biomass feedstock scenarios and demonstration farm performance. Synthesize findings with Goals 1 and 3 to characterize the system gaps between current conditions and the alternative pathways articulated by stakeholders in OBJ 3.1.

Outputs: Subfield, field, and aggregated simulation results of multiple production scenarios. Identification of bottlenecks/tradeoffs in herbaceous biomass systems; assessment of risks and uncertainty. Ten datasets and 10 final reports to farmer cooperators (one per cooperator).

Limitations: Early conceptual harmonization among teams and timely data provision will be critical to stay on task so models can be refined in Y2-Y4 and final analysis produced in Y4-Y5.

OBJ 2.4. Develop leadership within the agricultural community (Comito, Ciolkosz, Heaton, Helmers, Karsten)

Rationale: We will include a broader suite of stakeholders by increasing farmer/landowner leadership through demonstration partnerships, field days, and farmer-to-farmer networks, and building on-the-ground capacity through bottom-up engagement of farm advisors (e.g., Extension, CCAs, technical service providers), conservation professionals (e.g., private sector and government employees), and agricultural retailers. Pennsylvania farmers who have biodigesters and manage AD digestate will have venues to convey their experience and expertise. The team will conduct a series of events starting in Y1 with these stakeholders to gauge their understanding of the bioeconomy. Programming tailored to each state's needs will be developed in collaboration with Iowa Learning Farms (ILF).

Methods/Work Plan: Task 2.4.1. Conduct 8 listening sessions (4 in IA; 4 in PA) with up to 25 farmers in each session in Y1. These invitation-only sessions will focus on developing farmer partners and determine what farmers/landowners need to participate in AD value chains. Sessions will be transcribed and summaries will be shared with the C-CHANGE team to inform stakeholder workshops, focus groups, courses, and business case studies. Task 2.4.2. Hold 8 Rapid Needs Assessment and Response (RNR)[159] winter workshops in Y1 (4 in IA; 4 in PA) with on-the-ground stakeholders to assess their understanding of the AD value chain. Task 2.4.3. Interested farmers will form a leadership group by participating in a leadership circle (two per state; Y2 and Y4). Task 2.4.4. Partner with commercial farmers to establish 10 demonstrations on their land (6 in IA; 1 in MO; 3 in PA). Low profitability/highly vulnerable areas will be converted to perennial vegetation or winter cover. Farmer partners will convert desired areas and we will assess changes in performance over time (OBJ 2.2). Task 2.4.5. Researchers/graduate/undergraduates will meet informally on an annual basis with farmer partners (at their farms) to discuss their individual biomass crop yield, soil and nutrient retention, and other issues of interest identified in farmer leadership circles, creating a feedback loop for researchers and farmer partners. Task 2.4.6. Disseminate project findings through field days (10 in IA, 8 in PA in Y1-Y5), webinars (1 per year), and presentations (7 presentations per state annually in Y2-Y5). Field days, webinars, and presentations will focus on various components of the project for a total of 56 presentations given at the multiple conferences and educational series conducted by Extension in IA and PA. Task 2.4.7. Conduct 1 short course on the AD bioeconomy for soil and water CCA credit in PA where there are many active digesters.

Outputs: 8 listening sessions, 8 RNRs, 10 on-farm demonstration sites, 2 leadership circle meetings, 50 individual farmer meetings, 40 demonstration farm reports, 16 field days, 56 presentations, 1 short course.

Limitations: Farmers may drop out of the program because of time constraints, lack of interest, or other factors. We will reduce chances of dropout by providing trained, dedicated project personnel to foster and maintain farmer relationships.

GOAL 3 – Advance the biobased value chain through stakeholder engagement

Effecting change in complex social-agroecological systems requires careful attention to the perspectives and interests of stakeholders[160,161] and engagement change agents in transdisciplinary partnerships that build pathways to change.[162] Goal 3 will complement Goal 2 work with farmers and their local advisors by engaging value chain stakeholders in: (1) iterative processes that advance shared visions for investment, infrastructure, market, and workforce development in the new value chain; (2) evaluation of feasibility of alternative value chain scenarios; and (3) work toward consensus on policy and actions needed to transform the value chain.

OBJ 3.1. Engage stakeholders toward a shared vision for value chain transformation (Arbuckle, Hinrichs, Fowler)

Rationale: State-of-the art stakeholder engagement processes employ complementary qualitative methods to conduct comprehensive assessments of contextual factors that may influence stakeholders' willingness to participate.[163,164] Such baseline assessments, in turn, inform social learning processes that bring key stakeholders together in facilitated spaces to employ data, predictive models, preference deliberation, consensus-building, and creativity to work toward shared visions and commitments to actions.[69,70,163,165–167]

Question: How will stakeholders' perspectives and interests regarding different potential value chain pathways coalesce (or not) into shared visions of a new biobased value chain?

Methods/Work Plan: OBJ 3.1.1. Conduct in-depth interviews with key actors (~50) to assess perspectives on potential biobased value chain transformation pathways. Actors will include: (1) private sector firms including farm management (e.g., Peoples Company) agronomic input and service suppliers (e.g., Land O'Lakes WinField), livestock integrators and processors (e.g., Smithfield), grain handlers and processors (e.g., Feed Energy), and biofuels/products firms (e.g., Dominion Energy); (2) public sector actors (agricultural and conservation agencies, Extension, municipalities); and (3) NGOs (farmer organizations, commodity groups, rural economic development, and environmental groups. Task 3.1.2. Analyze stakeholder interviews from Task 3.1.1 and synthesize with results from OBJ 2.4 farmer/advisor assessments to inform two sets of workshops. Task 3.1.3. Convene key actors interviewed in Task 3.1.1 for a first round of value chain workshops (1 in IA, 1 in PA) to construct 2-4 value chain scenarios. Task 3.1.4. Provide results from interviews and workshops to OBJ 3.2 investigators to conduct post-workshop integrated modeling analyses of regional impacts of scenarios. Task 3.1.5. Conduct workshops 2 (1 in IA, 1 in PA) to facilitate (1) key actors' review of modeled impacts of scenarios to build consensus on value chain transitions, and (2) a white paper outlining policy changes to catalyze rapid development of the new value chain.

Outputs: 1 interview database, 4 workshop transcripts, 1 workshop report, 1 policy white paper.

Limitations: Because social learning activities require stakeholder willingness to participate constructively, a potential limitation/pitfall is refusal to participate or inability to come to consensus. In that case, we will purposefully select a small but diverse panel of experts (3-5) from workshop participants to constructively help us improve a set of illustrative, contrasting scenarios.

OBJ 3.2 Quantify the value of products and services derived from the new value chain (Tyndall, Swenson, Niemi)

Rationale: Calibrating integrated modeling platforms with our stakeholder data leads to more robust predictions of social-agroecological system transformations, and can guide both consensus and policies for an emerging bioeconomy.[168] Likewise, comprehensive private financial and public economic understanding is required for stakeholder buy-in, public/private investment and business emergence, infrastructure expansion, and integrative policy.[169,170]

Question: What value/tradeoffs/risks do alternative value chains offer for society?

Methods and Work Plan: Task 3.2.1. Integrate stakeholder data from OBJ 2.4 and OBJ 3.1 to develop alternative potential land use configurations. Task 3.2.2. Input-output[171] and ecosystem service modeling[172] will combine alternative land use data layers from stakeholder workshops (OBJ 3.1) with production and financial data associated with new cropping choices (OBJ 2.1, 2.3) and feedstock bioprocessing systems (OBJ 1.1) to determine primary and secondary regional economic outcomes. Compare results for current and alternative value chains to determine changes in regional economic activity. Sensitivity analysis will be based on variable market prices, yield conditions, discount rates, and farmer participation to explore system conditions under risk and uncertainty stressors. Conduct a public benefit-to-cost assessment on ecosystem service outcomes characterized, scaled, and measured in GOALS 1 and 2. Updated regionally relevant benefit-transfer data[173] will monetize social benefits of enhanced ecosystem functionality including nutrient retention and carbon storage. Task 3.2.3. Integrate model outputs to characterize system gaps between current and alternative pathways articulated by OBJ 3.1 stakeholders.

Outputs: 3 primary data sets (system economic multipliers, regional feedstock enterprise budgets, meta-analysis data for regional benefit transfer purposes); a comprehensive economic impact analysis; 3 reports detailing a private farm-scale financial analysis, an overview and monetization of social benefits, and an integrated benefit to cost assessment of various land use scenarios.

Limitations: This integrated assessment depends on inputs from many other areas of the project. Regular meetings will ensure timely data sharing.

OBJ 3.3 – Cultivate next generation leadership for the value chain (Schulte Moore, Hill, Campbell, Gagnon, Johnson, Kimle, Richard)

Rationale: The problems and potential solutions described in this proposal are transdisciplinary, complex, and challenging. They are also interesting and accessible for younger learners.[174,175] We will prepare the next generation of bioeconomy professionals by leveraging existing ISU and PSU education programs involving precollege students and teachers and undergraduates with university research and entrepreneurial activities. ISU's Science Bound program and PSU's Center for Science And The Schools (CSATS) engage precollege teachers and students, particularly those from traditionally underserved rural and urban communities, to develop the talent pipeline coming into universities. ISU's Agricultural Entrepreneurship Initiative and PSU's Entrepreneurship and Innovation train and mentor students to bring innovations to the marketplace. Educational activities will parallel the research activities of C-CHANGE faculty, staff, and industry partners, but appropriately complex for the respective participants.

Methods/Work Plan: Task 3.3.1. Starting in Y1, collaborate with professionals in communications, web design, videography, and animation to generate educational materials for use in formal and non-formal educational settings, as well as through mass media. Materials will include a graphics, visualizations, and videos that clearly explain AD and associated products, bioproduct engineering, herbaceous biomass crops, modeling, and other project topics. Videos will feature students where appropriate and permitted. Task 3.3.2. Engage middle and high school teachers and students from underserved populations in urban and rural settings in projects that utilize C-CHANGE as a means of teaching disciplinary STEM content. In Iowa in Y1-Y5, 650 high school and middle school students participating in ISU's Science Bound program will engage in capstone projects that can be entered in their school and district science fairs. Twenty-five ISU undergraduates (C-CHANGE Ambassadors) will help guide the students in these projects serving as mentors and advisors. In Pennsylvania in Y1-Y2, four precollege teachers will be hosted by C-CHANGE faculty and closely mentored by their graduate students in PSU CSATS' 6-week Research Experiences for Teachers (RET). These teachers will be integrated into an existing RET program and will assist CSATS and C-CHANGE faculty and graduate students in developing and implementing weeklong workshops for 51 teachers in Y3-5, incorporating some of the curriculum developed during their RETs, which will be based on the content and practices involved in C-CHANGE. Each teacher reaches an average of 120 students, for a total reach of 6,600 students. Task 3.3.3. Update education modules annually in Y2-Y5 based on evaluation information. Task 3.3.4. Place 10 (5 in IA, 5 in PA) high school students per year for Y1-Y5 with university researchers and instructors through summer programs (CyBound at ISU, Central Pennsylvania Institute of Science and Technology, a local career and technical school for high school and adult learners in PA). The high school students will participate in trainings, lab experiments, field data collection, data entry, and outreach events. Students will receive training in innovation and entrepreneurship through Change Maker Academy at ISU and Ag Springboard at PSU. Task 3.3.5. In each year of the project, 6 or more undergraduates will participate in a year-long entrepreneurship program at each university: Change Maker Academy at ISU, Ag Springboard at PSU. Student teams will be mentored by faculty in ISU's Agricultural Entrepreneurship Initiative and PSU's Entrepreneurship and Innovation Program to bring their ideas to market. Task 3.3.6. Support 12 or more undergraduates annually employed by C-CHANGE. We will host monthly round table discussions at ISU and PSU, pairing undergraduates with C-CHANGE experts to discuss student professional development, work processes, outputs, and outcomes.

Outputs: 8 videos, 10 graphics, 3 animations, 8 new education modules, programming for 59 high school teachers, 7,250 high school students, and 165 undergraduate students.

Outcomes: A workforce more educated about the bioeconomy supporting an expanded bioeconomy that includes the C-CHANGE value chain.

Limitations: Potential dropout will be minimized by leveraging long-standing programs and their relationships with schools (ISU Science Bound, PSU CSATS) and entrepreneurial communities (ISU Agricultural Entrepreneurship Initiative, PSU Entrepreneurship and Innovation).

D. EVALUATION PLAN

This project will use formative evaluation using multiple methods to provide a positive feedback loops for continual improvement to programming in each year of the grant and summative evaluation in the final year.[176] All C-CHANGE events will be evaluated with descriptive statistics (number of attendees, participant organizational affiliation, number of hours of contact) and use of published materials will be tracked through web analytics. Commercialization support short courses will be evaluated through pre/post surveys. Farmer partners will be interviewed by Extension team members at the beginning, middle, and end of the project to understand individual questions, concerns, innovations, and insights. Digester Days and field days will be evaluated by Extension team members using ILF's established four-step protocol[177]. Education team members will conduct a pre-/post-assessments to evaluate participant and host experiences and the development of STEM and entrepreneurial identity.[175,178,179] Progression of teacher or student work, community impact, and understanding of scientific content will further be assessed using experimental logs and posters to code the ideas. The undergraduate intern program will incorporate an assessment loop where students regularly meet with their program/research mentors to evaluate professional development. Additional evaluation includes self-efficacy assessment (confidence, wherewithal) for participants. The external program evaluator will conduct interviews with 50 team members, collaborators, and event participants annually over the period of 5 years regarding program efficacy and progress toward meeting goals and objectives. The evaluator will provide annual reports to the team to ensure feedback loops between and alignment across the project's activities, management structures, and outcomes. An end-of-project survey of project education and outreach participants (n=400) will additionally be developed and administered in Y5, and a summative evaluation report will be delivered.

E. PROJECT TIME TABLE

Project Timeline by Year & Quarters	Research	**2020-21**				**2021-22**				**2022-23**				**2023-24**				**2024-25**			
Q1=O,N,D; Q2=J,F,M; Q3=A,M,J; Q4=J,A,S	Education																				
(M = Milestone; D=Deliverable)	Extension	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
GOAL1 - Advance the AD of herbaceous feedstocks for RNG and associated products																					
OBJ1.1 - Identify pathways that improve RNG		M			D				D												D
OBJ1.2 - Investigate viable approaches to intensification						M			D				D				D				
OBJ1.3 - Characterize AD at pilot and commercial scales										M			D				D				D
OBJ1.4 - Catalyze through commercialization supports					D				D				D				D				D
GOAL2 - Advance productive, profitable, and sustainable sources of herbaceous feedstocks																					
OBJ2.1 - Collate existing datasets		M			D			M	D												
OBJ2.2 - Collect gap-filling data		M							M			D	D			D	D			D	D
OBJ2.3 - Improve model predictions														M			D				D
OBJ2.4 - Develop leadership in the agricultural community		M			M	D			D				D				D				D
GOAL3 - Advance the new bio-based value you chain through societal engagement																					
OBJ3.1 - Engage stakeholders toward a shared vision		M			D			M	D							M	D				
OBJ3.2 - Quantify the value of products and services								M							D			M			D
OBJ3.3 - Cultivate next generation support and leadership		M		M	D			M	D			M	D			M	D			M	D
Project Management																					
PM1 - All hands, leadership, executive, and advisory meetings		M	D	M	D	M	D	D	D	M	D	D	D	M	D	D	D	M	D	D	D
PM2 - Data QAQC, curation, archival		M			D				D				D				D				D
PM3 - Task, project, and administrative evaluation		M	D	M	D	M	D	M	D	M	D	M	D	M	D	D	M	M	D	M	D
PM4 - Final evaluation and program report																		M			D

REFERENCES

1. Ketchen Jr, D. J. & Hult, G. T. M. Bridging organization theory and supply chain management: The case of best value supply chains. *J. Oper. Manag.* **25**, 573–580 (2007).
2. USDA NASS [US Department of Agriculture National Agricultural Statistics Service]. Quick stats. *USDA NASS quick stats.* (2018). Available at: https://www.nass.usda.gov/Quick_Stats/. (Accessed: 23rd September 2019)
3. Pleima, B. Biogas to RNG projects: who, how and why. *Biocycle* **60**, 38 (2019).
4. USDA. Farm labor: number of farms and workers by decade, US. (2019). Available at: https://www.nass.usda.gov/Charts_and_Maps/Farm_Labor/fl_frmwk.php. (Accessed: 24th September 2019)
5. Morton, L. W., Hobbs, J. & Arbuckle, J. G. Shifts in farmer uncertainty over time about sustainable farming practices and modern farming's reliance on commercial fertilizers, insecticides, and herbicides. *J. soil water Conserv.* **68**, 1–12 (2013).
6. Lobao, L. & Stofferahn, C. W. The community effects of industrialized farming: Social science research and challenges to corporate farming laws. *Agric. Human Values* **25**, 219–240 (2008).
7. Tegtmeier, E. M. & Duffy, M. D. External costs of agricultural production in the United States. *Int. J. Agric. Sustain.* **2**, 1–20 (2004).
8. Veenstra, J. J. & Burras, C. L. Effects of agriculture on the classification of Black soils in the Midwestern United States. *Can. J. Soil Sci.* **92**, 403–411 (2012).
9. Montgomery, D. R. *Dirt: the erosion of civilizations, 2nd edition*. (University of California Press, 2012).
10. Donham, K. J. Community and occupational health concerns in pork production: a review. *J Anim Sci* **88**, E102-11 (2010).
11. Borlée, F. *et al.* Air pollution from livestock farms is associated with airway obstruction in neighboring residents. *Am. J. Respir. Crit. Care Med.* **196**, 1152–1161 (2017).
12. De Vries, J. W., Groenestein, C. M. & De Boer, I. J. M. Environmental consequences of processing manure to produce mineral fertilizer and bio-energy. *J. Environ. Manage.* **102**, 173–183 (2012).
13. Turner, R. E. & Rabalais, N. N. Nitrogen and phosphorus phytoplankton growth limitation in the northern Gulf of Mexico. *Aquat. Microb. Ecol.* **68**, 159–169 (2013).
14. Pennino, M. J., Compton, J. E. & Leibowitz, S. G. Trends in drinking water nitrate violations across the United States. *Environ. Sci. Technol.* **51**, 13450–13460 (2017).
15. Tang, C. *et al.* Economic benefits of nitrogen reductions in Iowa. 29 (2018).
16. Keisman, J. L. D. *et al. Manure and fertilizer inputs to land in the Chesapeake Bay watershed, 1950–2012*. *Scientific Investigations Report* (2018). doi:10.3133/sir20185022
17. US EPA & US Environmental Protection Agency. *2015 Report to Congress*. *Biennial Report: Mississippi River/Gulf of Mexico Watershed Nutrient Task Force* (2015).
18. Spivak, M., Mader, E., Vaughan, M. & Euliss Jr, N. H. The plight of the bees. *Environ. Sci. Technol.* **45**, 34–38 (2011).
19. Thogmartin, W. E. *et al.* Restoring monarch butterfly habitat in the Midwestern US: 'all hands on deck'. *Environ. Res. Lett.* **12**, 74005 (2017).
20. Rosenberg, K. V *et al.* Decline of the North American avifauna. *Science (80-.).* eaaw1313

(2019).

21. Lynd, L. R. The grand challenge of cellulosic biofuels. *Nat. Biotechnol.* **35**, 912 (2017).
22. USDA ERS. U.S. bioenergy statistics. (2019). Available at: https://www.ers.usda.gov/data-products/us-bioenergy-statistics/. (Accessed: 24th September 2019)
23. Abbasi, T., Tauseef, S. M. & Abbasi, S. A. A brief history of anaerobic digestion and "biogas". in *Biogas energy* 11–23 (Springer, 2012).
24. Appels, L. *et al.* Anaerobic digestion in global bio-energy production: potential and research challenges. *Renew. Sustain. Energy Rev.* **15**, 4295–4301 (2011).
25. Bassett, J. *et al. Anaerobic digestion and its applications*. (U.S. Environmental Protection Agency, 2015).
26. Cucchiella, F., Adamo, I. & Gastaldi, M. Biomethane: A renewable resource as vehicle fuel. *Resources* **6**, 58 (2017).
27. Van Meerbeek, K. *et al.* Energy potential for combustion and anaerobic digestion of biomass from low-input high-diversity systems in conservation areas. *GCB Bioenergy* **7**, 888–898 (2015).
28. US EPA & US Environmental Protection Agency. *Biofuels and the environment - second triennial report to congress*. (2018).
29. Hahn, H., Krautkremer, B., Hartmann, K. & Wachendorf, M. Review of concepts for a demand-driven biogas supply for flexible power generation. *Renew. Sustain. Energy Rev.* **29**, 383–393 (2014).
30. Pless, J., Arent, D. J., Logan, J., Cochran, J. & Zinaman, O. Quantifying the value of investing in distributed natural gas and renewable electricity systems as complements: Applications of discounted cash flow and real options analysis with stochastic inputs. *Energy Policy* **97**, 378–390 (2016).
31. Lee, A., Zinaman, O. & Logan, J. *Opportunities for synergy between natural gas and renewable energy in the electric power and transportation sectors*. (National Renewable Energy Lab.(NREL), Golden, CO (United States), 2012).
32. Holtzapple, M. T. & Granda, C. B. Carboxylate platform: the MixAlco process part 1: comparison of three biomass conversion platforms. *Appl Biochem Biotechnol* **156**, 95–106 (2009).
33. Granda, C. B., Holtzapple, M. T., Luce, G., Searcy, K. & Mamrosh, D. L. Carboxylate platform: the MixAlco process part 2: process economics. *Appl. Biochem. Biotechnol.* **156**, 107–124 (2009).
34. Urban, C. *et al.* Production of drop-in fuels from biomass at high selectivity by combined microbial and electrochemical conversion. *Energy Environ. Sci.* **10**, 2231–2244 (2017).
35. Angenent, L. T. *et al.* Integrating electrochemical, biological, physical, and thermochemical process units to expand the applicability of anaerobic digestion. *Bioresour. Technol.* **247**, 1085–1094 (2018).
36. Weber, R. S. *et al.* Modularized production of fuels and other value-added products from distributed, wasted, or stranded feedstocks. *Wiley Interdiscip. Rev. Energy Environ.* **e308**, (2018).
37. Laird, D. A., Brown, R. C., Amonette, J. E. & Lehmann, J. Review of the pyrolysis

platform for coproducing bio-oil and biochar. *Biofuels, Bioprod. biorefining* **3**, 547–562 (2009).

38. Laird, D. A. The charcoal vision: A win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agron. J.* **100**, 178–181 (2008).
39. Vaneeckhaute, C. *et al.* Closing nutrient loops through decentralized anaerobic digestion of organic residues in agricultural regions: A multi-dimensional sustainability assessment. *Resour. Conserv. Recycl.* **1**, 110–117 (2018).
40. Lijó, L. *et al.* Eco-efficiency assessment of farm-scaled biogas plants. *Bioresour. Technol.* **237**, 146–155 (2017).
41. Pandey, P. K. & Soupir, M. L. Escherichia coli inactivation kinetics in anaerobic digestion of dairy manure under moderate, mesophilic and thermophilic temperatures. *AMB express* **1**, 18 (2011).
42. Orzi, V. *et al.* The role of biological processes in reducing both odor impact and pathogen content during mesophilic anaerobic digestion. *Sci. Total Environ.* **526**, 116–126 (2015).
43. US EPA & US Environmental Protection Agency. *Market opportunities for biogas recovery systems at U.S. livestock facilities*. (2018).
44. Murphy, J., Braun, R., Weiland, P. & Wellinger, A. Energy from biogas. (2011). Available at: https://www.ieabioenergy.com/wp-content/uploads/2011/10/Update_Energy_crop_2011.pdf.
45. US EPA. AgStar Database. (2019). Available at: https://www.epa.gov/agstar/livestock-anaerobic-digester-database. (Accessed: 24th September 2019)
46. Wall, D. M., Dumont, J. D., Murphy, J. D. & International Energy Agency. *Green Gas: Facilitating a future green gas grid through the production of renewable gas*. (IEA Bioenergy Task 37, 2018).
47. Thran, D. *et al. Biomethane: Status and factors affecting market development and trade*. (A joint study by IEA Task 37 and Task 40, 2014).
48. Hendriks, A. & Zeeman, G. Pretreatments to enhance the digestibility of lignocellulosic biomass. *Bioresour. Technol.* **100**, 10–18 (2009).
49. Paye, J. M. D. *et al.* Biological lignocellulose solubilization: comparative evaluation of biocatalysts and enhancement via cotreatment. *Biotechnol. Biofuels* **9**, 8 (2016).
50. Aui, A., Li, W. & Wright, M. M. Techno-economic and life cycle analysis of a farm-scale anaerobic digestion plant in Iowa. *Waste Manag.* **89**, 154–164 (2019).
51. Ahn, H. K., Smith, M. C., Kondrad, S. L. & White, J. W. Evaluation of biogas production potential by dry anaerobic digestion of switchgrass--animal manure mixtures. *Appl Biochem Biotechnol* **160**, 965–975 (2010).
52. Yang, L. C., Xu, F. Q., Ge, X. M. & Li, Y. B. Challenges and strategies for solid-state anaerobic digestion of lignocellulosic biomass. *Renew. Sustain. Energy Rev.* **44**, 824–834 (2015).
53. Kim, Y. H., Park, L. K., Yiacoumi, S. & Tsouris, C. Modular chemical process intensification: A review. *Annu Rev Chem Biomol Eng* **8**, 359–380 (2017).
54. Olivos-Suarez, A. I. *et al.* Strategies for the direct catalytic valorization of methane using heterogeneous catalysis: challenges and opportunities. *Acs Catal.* **6**, 2965–2981 (2016).

55. Gloy, B. A. & Dressler, J. B. Financial barriers to the adoption of anaerobic digestion on US livestock operations. *Agric. Financ. Rev.* **70**, 157–168 (2010).

56. Wilkinson, K. G. A comparison of the drivers influencing adoption of on-farm anaerobic digestion in Germany and Australia. *Biomass and bioenergy* **35**, 1613–1622 (2011).

57. Vasco-Correa, J., Khanal, S., Manandhar, A. & Shah, A. Anaerobic digestion for bioenergy production: Global status, environmental and techno-economic implications, and government policies. *Bioresour. Technol.* **247**, 1015–1026 (2018).

58. Fagerstrom, A., Al Seadi, T., Rasi, S., Briseid, T. & International Energy Agency. *The role of anaerobic digestion and biogas in the circular economy*. **8**, (IEA Bioenergy Task 37, 2018).

59. Dale, B. E. *et al.* Biogasdoneright^{TM}: an innovative new system is commercialized in Italy. *Biofuels, Bioprod. Biorefining* **10**, 341–345 (2016).

60. Valenti, F. *et al.* Anaerobic co-digestion of multiple agricultural residues to enhance biogas production in southern Italy. *Waste Manag.* **78**, 151–157 (2018).

61. Freese, B. Successful farming special: how Smithfield saved the worst hog farm in America. (2018). Available at: https://www.agriculture.com/livestock/pork-powerhouses/how-smithfield-saved-the-worst-hog-farm-in-america.

62. Arbuckle, J. *Iowa Farm and Rural Life Poll: 2018 Summary Report*. (2019).

63. Nowatzke, L. & Arbuckle, J. G. J. *Iowa farmers and the Iowa Nutrient Reduction Strategy: 2015 survey results*. (2016).

64. Loy J. Hobbs, J.G. Arbuckle Jr., L.W. Morton, L.S. Prokopy, T. Haigh, T. Knoot, C. Knutson, A. Saylor Mase, J. McGuire, J. Tyndall, and M. Widhalm., A. & USDA National Institute of Food and Agriculture. *Farmer perspectives on agriculture and weather variability in the Corn Belt: A statistical atlas, Volume 1.* (Cropping Systems Coordinated Agricultural Project (CSCAP): Climate Change, Mitigation, and Adaptation in Corn-based Cropping Systems., 2013).

65. Roesch-McNally, G. E., Arbuckle, J. G. & Tyndall, J. C. Barriers to implementing climate resilient agricultural strategies: The case of crop diversification in the US Corn Belt. *Glob. Environ. Chang.* **48**, 206–215 (2018).

66. Tyndall, J. C., Berg, E. J. & Colletti, J. P. Corn stover as a biofuel feedstock in Iowa's bio-economy: An Iowa farmer survey. *Biomass and Bioenergy* (2011). doi:10.1016/j.biombioe.2010.08.049

67. Zimmerman, E. K., Tyndall, J. C., Schulte, L. A. & Larsen, G. L. D. Farmer and farmland owner views on spatial targeting for soil conservation and water quality. *Water Resour. Res.* (2019).

68. Enloe, S. K., Schulte, L. A. & Tyndall, J. C. Public–private partnerships working beyond scale challenges toward water quality improvements from private lands. *Environ. Manage.* **60**, 574–587 (2017).

69. Atwell, R. C., Schulte, L. A. & Westphal, L. M. Landscape, community, countryside: Linking biophysical and social scales in US Corn Belt agricultural landscapes. *Landsc. Ecol.* **24**, 791–806 (2009).

70. Atwell, R. C., Schulte, L. A. & Westphal, L. M. How to build multifunctional agricultural landscapes in the U.S. Corn Belt: add perennials and partnerships. *Land use policy* **27**,

1082–1090 (2010).

71. Eaton, W. M., Burnham, M., Hinrichs, C. C., Selfa, T. & Yang, S. How do sociocultural factors shape rural landowner responses to the prospect of perennial bioenergy crops? *Landsc. Urban Plan.* **175**, 195–204 (2018).

72. Burnham, M., Eaton, W., Selfa, T., Hinrichs, C. & Feldpausch-Parker, A. The politics of imaginaries and bioenergy sub-niches in the emerging Northeast U.S. bioenergy economy. *Geoforum* **82**, 66–76 (2017).

73. Eaton, W. M., Burnham, M., Hinrichs, C. C. & Selfa, T. Bioenergy experts and their imagined "obligatory publics" in the United States: Implications for public engagement and participation. *Energy Res. Soc. Sci.* **25**, 65–75 (2017).

74. Zhang, Y. & Wright, M. M. Product selection and supply chain optimization for fast pyrolysis and biorefinery system. *Ind. Eng. Chem. Res.* **53**, 19987–19999 (2014).

75. Hu, W., Dang, Q., Rover, M., Brown, R. C. & Wright, M. M. Comparative techno-economic analysis of advanced biofuels, biochemicals, and hydrocarbon chemicals via the fast pyrolysis platform. *Biofuels* **7**, 57–67 (2016).

76. Dang, Q., Wright, M. M. & Brown, R. C. Ultra-low carbon emissions from coal-fired power plants through bio-oil co-firing and biochar sequestration. *Env. Sci Technol.* **49**, 14688–95 (2015).

77. Brandes, E. *et al.* Targeted subfield switchgrass integration could improve the farm economy, water quality, and bioenergy feedstock production. *GCB Bioenergy* **10**, 199–212 (2018).

78. Brandes, E. *et al.* Subfield profitability analysis reveals an economic case for cropland diversification. *Environ. Res. Lett.* **11**, 014009 (2016).

79. McNunn, G., Heaton, E., Archontoulis, S., Licht, M. & VanLoocke, A. A crop modeling approach for precision cost-benefit analysis of variable seeding and nitrogen application rates. *Front. Sustain. Food Syst.*

80. Holzworth, D. P. *et al.* APSIM–evolution towards a new generation of agricultural systems simulation. *Bioresour. Technol.* **3**, 547–562 (2012).

81. Togliatti, K., Archontoulis, S. V, Dietzel, R., Puntel, L. & VanLoocke, A. How does inclusion of weather forecasting impact in-season crop model predictions? *F. Crop. Res.* **214**, 261–272 (2017).

82. Jin, Z. *et al.* The combined and separate impacts of climate extremes on the current and future US rainfed maize and soybean production under elevated CO2. *Glob. Chang. Biol.* **23**, 2687–2704 (2017).

83. Puntel, L. A. *et al.* A systems modeling approach to forecast corn economic optimum nitrogen rate. *Front. Plant Sci.* **9**, 436 (2018).

84. White, C. M., Kemanian, A. R. & Kaye, J. P. Implications of carbon saturation model structures for simulated nitrogen mineralization dynamics. *Biogeosciences* **11**, 6725–6738 (2014).

85. Kemanian, A. R. & Stöckle, C. O. C-Farm: a simple model to evaluate the carbon balance of soil profiles. *Eur. J. Agron.* **32**, 22–29 (2010).

86. Stöckle, C. O., Kemanian, A. R. & Kremer, C. On the use of radiation- and water-use efficiency for biomass production models. in *Response of crops to limited water:*

understanding and modeling water stress effects on plant growth processes (eds. Ahuja, L. R., Reddy, V. R., Saseendran, S. A. & Yu, Q.) 39–58 (American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, 2008). doi:10.2134/advagricsystmodel1.c2

87. Jarchow, M. E. *et al.* Trade-offs among agronomic, energetic, and environmental performance characteristics of corn and prairie bioenergy cropping systems. *GCB Bioenergy* **7**, 57–71 (2015).

88. Dietzel, R., Jarchow, M. E. & Liebman, M. Above- and belowground growth, biomass, and nitrogen use in maize and reconstructed prairie cropping systems. *Crop Sci.* **55**, 910–923 (2015).

89. Daigh, A. L. M. *et al.* Subsurface drainage nitrate and total reactive phosphorus losses in bioenergy-based prairies and corn systems. *J. Environ. Qual.* **44**, 1638–46 (2015).

90. Ibrahim, M. A., Chua-Ona, T., Liebman, M. & Thompson, M. L. Soil organic carbon storage under biofuel cropping systems in a humid, continental climate. *Agron. J.* **110**, 1748–1753 (2018).

91. Amin, M. G. M., Karsten, H. D., Veith, T. L., Beegle, D. B. & Kleinman, P. J. Conservation dairy farming impact on water quality in a karst watershed in northeastern US. *Agric. Syst.* **165**, 187–196 (2018).

92. Snyder, E. M., Karsten, H. D., Curran, W. S., Malcolm, G. M. & Hyde, J. A. Green manure comparison between winter wheat and corn: weeds, yields, and economics. *Agron. J.* **108**, 2015–2025 (2016).

93. Malcolm, G. M., Camargo, G. G. T., Ishler, V. A., Richard, T. L. & Karsten, H. D. Energy and greenhouse gas analysis of northeast US dairy cropping systems. *Agric. Ecosyst. Environ.* **199**, 407–417 (2015).

94. Duncan, E. W., Kleinman, P. J. A., Beegle, D. B. & Rotz, C. A. Coupling dairy manure storage with injection to improve nitrogen management: Whole-farm simulation using the integrated farm system model. *Agric. Environ. Lett.* **2**, (2017).

95. Duncan, E. W., Dell, C. J., Kleinman, P. J. A. & Beegle, D. B. Nitrous oxide and ammonia emissions from injected and broadcast-applied dairy slurry. *J. Environ. Qual.* **46**, 36–44 (2017).

96. Duncan, E. W. *et al.* Development of field-scale lysimeters to assess management impacts on runoff. *Trans. Asabe* **60**, 419–429 (2017).

97. Jahanzad, E., Saporito, L. S., Karsten, H. D. & Kleinman, P. J. A. Varying influence of dairy manure injection on phosphorus loss in runoff over four years. *J. Environ. Qual.* **48**, 450–458 (2019).

98. Milliron, R. A., Karsten, H. D. & Beegle, D. B. Influence of dairy slurry manure application method, fall application-Timing, and winter rye management on nitrogen conservation. *Agron. J.* **111**, 995–1009 (2019).

99. Hill, J., Polasky, S., Nelson, E. & Tilman, D. Climate change and health costs of air emissions from biofuels and gasoline. *PNAS* (2009).

100. Dale, B. E. *et al.* Take a closer look: Biofuels can support environmental, economic and social goals. *Environmental Science and Technology* (2014). doi:10.1021/es5025433

101. Asbjornsen, H. *et al.* Targeting perennial vegetation in agricultural landscapes for

enhancing ecosystem services. *Renew. Agric. Food Syst.* **29**, 101–125 (2014).

102. Heggenstaller, A. H., Anex, R. P., Liebman, M., Sundberg, D. N. & Gibson, L. R. Productivity and nutrient dynamics in bioenergy double-cropping systems. *Agron. J.* **100**, 1740–1748 (2008).

103. Basso, B., Shuai, G., Zhang, J. & Robertson, G. P. Yield stability analysis reveals sources of large-scale nitrogen loss from the US Midwest. *Sci. Rep.* **9**, 5774 (2019).

104. Muth, D. J., Bryden, K. M. & Nelson, R. G. Sustainable agricultural residue removal for bioenergy: A spatially comprehensive US national assessment. *Appl. Energy* **102**, 403–417 (2013).

105. Anex, R. P., Lynd, L. R., Laser, M. S., Heggenstaller, A. H. & Liebman, M. Potential for enhanced nutrient cycling through coupling of agricultural and bioenergy systems. *Crop Sci.* **47**, 1327–1335 (2007).

106. Campo, B. G. del, Morris, M. D., Laird, D. A., Kieffer, M. M. & Brown, R. C. Optimizing the production of activated carbon from fast pyrolysis char. *Technology* **03**, 104–113 (2015).

107. Johnston, P. *et al.* A lignin-first strategy to recover hydroxycinnamic acids and improve cellulosic ethanol production from corn stover. *Biomass and Bioenergy* **In review**,

108. Lisowyj, M. & Wright, M. M. A review of biogas and an assessment of its economic impact and future role as a renewable energy source. *Rev. Chem. Eng.* **0**, (2018).

109. Milbrandt, A., Bush, B. & Melaina, M. *Biogas and hydrogen systems market assessment*. (National Renewable Energy Lab (NREL), Golden, CO, 2016).

110. US EPA. RIN trades and price information. (2019). Available at: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information. (Accessed: 24th September 2019)

111. Bonner, I. *et al.* Development of integrated bioenergy production systems using precision conservation and multicriteria decision analysis techniques. *J. Soil Water Conserv.* **71**, 182–193 (2016).

112. Basche, A. D. *et al.* Soil water improvements with the long-term use of a winter rye cover crop. *Agric. Water Manag.* (2016). doi:10.1016/j.agwat.2016.04.006

113. Dabney, S. M., Delgado, J. A. & Reeves, D. W. Using winter cover crops to improve soil and water quality. *Commun. Soil Sci. Plant Anal.* **32**, 1221–1250 (2001).

114. Helmers, M. J. *et al.* Sediment removal by prairie filter strips in row-cropped ephemeral watersheds. *J. Environ. Qual.* **41**, 1531–1539 (2012).

115. Schulte, L. *et al.* Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn-soybean croplands. *Proc. Natl. Acad. Sci.* **114**, 11247–11252 (2017).

116. Wilcoxen, C. A., Walk, J. W. & Ward, M. P. Use of cover crop fields by migratory and resident birds. *Agric. Ecosyst. Environ.* **252**, 42–50 (2018).

117. Feyereisen, G. W., Camargo, G. G. T., Baxter, R. E., Baker, J. M. & Richard, T. L. Cellulosic biofuel potential of a winter rye double crop across the US corn–soybean belt. *Agron. J.* **105**, 631–642 (2013).

118. USDA [US Department of Agriculture]. US Food Waste Challenge FAQs. (2019). Available at: https://www.usda.gov/oce/foodwaste/faqs.htm. (Accessed: 23rd September 2019)

119. Sawatdeenarunat, C., Surendra, K. C., Takara, D., Oechsner, H. & Khanal, S. K. Anaerobic digestion of lignocellulosic biomass: challenges and opportunities. *Bioresour. Technol.* **178**, 178–186 (2015).

120. Malone, R. W. *et al.* Harvesting fertilized rye cover crop: Simulated revenue, net energy, and drainage nitrogen loss. *Agric. Environ. Lett.* **3**, (2018).

121. Langholtz, M. H., Stokes, B. J. & Eaton, L. M. *2016 Billion-ton report: advancing domestic resources for a thriving bioeconomy*. **1**, (U.S. Department of Energy, 2016).

122. Liu, X. & Iutzi, F. Estimating the economic impact of increased cover crop seed sales in Illinois. *Economics of Cover Crops Webinar* (2015).

123. USDA NASS. 2017 Census of Agriculture State Profile: Iowa. (2017). Available at: https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/County_Profiles/Iowa/cp99019.pdf. (Accessed: 25th September 2019)

124. Brown, P. W. & Schulte, L. A. Agricultural landscape change (1937-2002) in three townships in Iowa, USA. *Landsc. Urban Plan.* **100**, 202–212 (2011).

125. Secchi, S., Gassman, P. W., Jha, M., Kurkalova, L. & Kling, C. L. Potential water quality changes due to corn expansion in the Upper Mississippi River Basin. *Ecol. Appl.* **21**, 1068–1084 (2011).

126. Jones, C. S., Nielsen, J. K., Schilling, K. E. & Weber, L. J. Iowa stream nitrate and the Gulf of Mexico. *PLoS One* **13**, e0195930 (2018).

127. IDALS [Iowa Department of Agriculture and Land Stewardship], IDNR [Iowa Department of Natural Resources] & ISU [Iowa State University]. *Iowa nutrient reduction strategy: a science and technology-based framework to assess and reduce nutrients to Iowa waters and the Gulf of Mexico*. (2013).

128. Grixti, J. C., Wong, L. T., Cameron, S. A. & Favret, C. Decline of bumble bees (Bombus) in the North American Midwest. *Biol. Conserv.* **142**, 75–84 (2009).

129. USDA NASS. 2017 Census of Agriculture State Profile: Missouri. (2017). Available at: https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/County_Profiles/Missouri/cp99029.pdf. (Accessed: 25th September 2019)

130. USDA NASS. 2017 US Census of Agriculture State Profile: Pennsylvania. (2017). Available at: https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/County_Profiles/Pennsylvania/cp99042.pdf. (Accessed: 25th September 2019)

131. Mississippi River/Gulf Hypoxia Nutrient Task Force. *Gulf Hypoxia Action Plan 2008 for Reducing Mitigating, And Controlling Hypoxia in the Northern Gulf of Mexico and Improving Water Quality in the Mississippi River Basin*. *Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds* (2008).

132. Pennsylvania Department of Environmental Protection. Phase 3 OF Pennsylvania's Chesapeake Bay Watershed Implementation Plan (WIP3). (2018). Available at: https://www.dep.pa.gov/Business/Water/Pennsylvania's Chesapeake Bay Program Office/WIP3/Pages/Phase-III-WIP-(Watershed-Implementation-Plans).aspx.

133. Amon, T. *et al.* Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations. *Bioresour. Technol.* **98**, 3204–3212 (2007).

134. Goodrich, P. Anaerobic digester systems for mid-sized dairy farms. *Minnesota Proj. St.*

Paul, MN 37 (2005).

135. Brown, D., Shi, J. & Li, Y. Comparison of solid-state to liquid anaerobic digestion of lignocellulosic feedstocks for biogas production. *Bioresour. Technol.* **124**, 379–386 (2012).
136. Li, Y., Park, S. Y. & Zhu, J. Solid-state anaerobic digestion for methane production from organic waste. *Renew. Sustain. energy Rev.* **15**, 821–826 (2011).
137. Chynoweth, D. P., Owens, J. M. & Legrand, R. Renewable methane from anaerobic digestion of biomass. *Renew. energy* **22**, 1–8 (2001).
138. Tian, L. *et al.* Identifying proper agitation interval to prevent floating layers formation of corn stover and improve biogas production in anaerobic digestion. *Bioresour. Technol.* **186**, 1–7 (2015).
139. Liang, X. *et al.* Development and characterization of stable anaerobic thermophilic methanogenic microbiomes fermenting switchgrass at decreasing residence times. *Biotechnol. Biofuels* **11**, 243 (2018).
140. Fernández-Rodríguez, J., Pérez, M. & Romero, L. I. Semicontinuous temperature-phased anaerobic digestion (TPAD) of organic fraction of municipal solid waste (OFMSW). Comparison with single-stage processes. *Chem. Eng. J.* **285**, 409–416 (2016).
141. Frigon, J.-C., Mehta, P. & Guiot, S. R. Impact of mechanical, chemical and enzymatic pre-treatments on the methane yield from the anaerobic digestion of switchgrass. *Biomass and Bioenergy* **36**, 1–11 (2012).
142. Balch, M. L. *et al.* Lignocellulose fermentation and residual solids characterization for senescent switchgrass fermentation by Clostridium thermocellum in the presence and absence of continuous in situ ball-milling. *Energy Environ. Sci.* **10**, 1252–1261 (2017).
143. Lewandowski, I. Securing a sustainable biomass supply in a growing bioeconomy. *Glob. Food Sec.* **6**, 34–42 (2015).
144. Dale, V. H., Kline, K. L., Richard, T. L., Karlen, D. L. & Belden, W. W. Bridging biofuel sustainability indicators and ecosystem services through stakeholder engagement. *Biomass and Bioenergy* **114**, 143–156 (2018).
145. Bansal, S. & Nagarajan, M. Product portfolio management with production flexibility in agribusiness. *Oper. Res.* **65**, 914–930 (2017).
146. Bansal, S., Gutierrez, G. J. & Keiser, J. R. Quantifying uncertainties and risks using managerial judgments in a dynamic new product development environment. *Prod. Oper. Manag.* **25**, 2010–2013 (2016).
147. Bustamante, M. A. *et al.* Co-composting of the solid fraction of anaerobic digestates, to obtain added-value materials for use in agriculture. *Biomass and bioenergy* **43**, 26–35 (2012).
148. Polin, J. P., Whitmer, L. E., Smith, R. G. & Brown, R. C. Process intensification of a fluidized bed pyrolyzer via autothermal operation. *TCS 2016: Symposium on Thermal and Catalytic Sciences for Biofuels and Biobased Products* (2016).
149. Masebinu, S. O., Akinlabi, E. T., Muzenda, E. & Aboyade, A. O. A review of biochar properties and their roles in mitigating challenges with anaerobic digestion. *Renew. Sustain. Energy Rev.* **103**, 291–307 (2019).
150. Liu, F. *et al.* Promoting direct interspecies electron transfer with activated carbon. *Energy*

Environ. Sci. **5**, 8982–8989 (2012).

151. Bisio, A. & Kabel, R. L. *Scaleup of chemical processes: Conversion from laboratory scale tests to successful commercial size design*. (Wiley New York, 1985).
152. Balachandra, P., Reddy, B. S. & Sudhakara Reddy, B. *Commercialisation of sustainable energy technologies commercialisation of sustainable energy technologies commercialisation of sustainable energy technologies*. (2007).
153. Pravia, M. V. *et al.* Soil carbon saturation, productivity, and carbon and nitrogen cycling in crop-pasture rotations. *Agric. Syst.* **171**, 13–22 (2019).
154. Martinez-Feria, R. A. *et al.* Linking crop-and soil-based approaches to evaluate system nitrogen-use efficiency and tradeoffs. *Agric. Ecosyst. Environ.* **256**, 131–143 (2018).
155. Liebman, M. & Schulte, L. A. Enhancing agroecosystem performance and resilience through increased diversification of landscapes and cropping systems. *Elementa* **3**, 41 (2015).
156. Dietze, M. C., Lebauer, D. S. & Kooper, R. O. B. On improving the communication between models and data. *Plant. Cell Environ.* **36**, 1575–1585 (2013).
157. Iowa State University. ISU data team. (2017). Available at: https://datateam.agron.iastate.edu/cscap/dl/#tab_data. (Accessed: 23rd September 2019)
158. Surendran Nair, S. *et al.* Bioenergy crop models: descriptions, data requirements, and future challenges. *Gcb Bioenergy* **4**, 620–633 (2012).
159. Comito, J., Case Haub, B. & Licht, M. Rapid needs assessment and response technique. *J. Ext.* **56**, 2TOT1 (2018).
160. Kretser, H. E., Beckmann, J. P. & Berger, J. A retrospective assessment of a failed collaborative process in conservation. *Environ. Manage.* **62**, 415–428 (2018).
161. Lavery, J. V. Building an evidence base for stakeholder engagement. *Science (80-.).* **361**, 554–556 (2018).
162. Dietz, T., Ostrom, E. & Stern, P. C. The struggle to govern the commons. *Science (80-.).* **302**, 1907–1912 (2003).
163. Ansell, C. & Gash, A. Collaborative governance in theory and practice. *J. public Adm. Res. theory* **18**, 543–571 (2008).
164. Herrero, P., Dedeurwaerdere, T. & Osinski, A. Design features for social learning in transformative transdisciplinary research. *Sustain. Sci.* **14**, 751–769 (2019).
165. Carpenter, S., Bennett, E. & Peterson, G. Scenarios for ecosystem services: an overview. *Ecol. Soc.* **11**, (2006).
166. Bennett, E. M. *et al.* Why global scenarios need ecology. *Front. Ecol. Environ.* **1**, 322–329 (2003).
167. Peterson, G. D., Cumming, G. S. & Carpenter, S. R. Scenario planning: a tool for conservation in an uncertain world. *Conserv. Biol.* **17**, 358–366 (2003).
168. Kling, C. L. *et al.* Research needs and challenges in the FEW system: Coupling economic models with agronomic, hydrologic, and bioenergy models for sustainable food, energy, and water systems. (2016).
169. Baumber, A. Enhancing ecosystem services through targeted bioenergy support policies. *Ecosyst. Serv.* **26**, 98–110 (2017).

170. Guerry, A. D. *et al.* Natural capital and ecosystem services informing decisions: From promise to practice. *Proc. Natl. Acad. Sci.* **112**, 7348–7355 (2015).

171. Miller, R. E. & Blair, P. D. *Input-output analysis: foundations and extensions*. (Cambridge Uversity Press, 2009).

172. Mishra, S. K. *et al.* Valuation of ecosystem services in alternative bioenergy landscape scenarios. *GCB Bioenergy* **11**, 748–762 (2019).

173. Hoque, M. & Kling, C. L. Economic valuation of ecosystem benefits from conservation practices targeted in Iowa nutrient reduction strategy 2013: A non market valuation approach. (2016).

174. NRC [National Research Council]. *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. (National Academies Press, 2012).

175. Williams, M. M. & George-Jackson, C. Using and doing science: Gender, self-efficacy, and science identity of undergraduate students in STEM. *J. Women Minor. Sci. Eng.* **20**, (2014).

176. Guskey, T. R. Does it make a difference? Evaluating professional development. *Educ. Leadersh.* **59**, 45 (2002).

177. [ILF] Iowa Learning Farms. *Iowa Learning Farms field day toolkit*. (2016).

178. Carlone, H. B. & Johnson, A. Understanding the science experiences of successful women of color: Science identity as an analytic lens. *J. Res. Sci. Teach. Off. J. Natl. Assoc. Res. Sci. Teach.* **44**, 1187–1218 (2007).

179. Downing, S. The social construction of entrepreneurship: Narrative and dramatic processes in the coproduction of organizations and identities. *Entrep. theory Pract.* **29**, 185–204 (2005).

LOGIC MODEL FOR INTEGRATED PROGRAM

Project: Schulte et al.: Consortium for Cultivating Human And Naturally reGenerative Enterprises (C-CHANGE)
Goal: To advance a new biobased value chain based on the production of renewable natural gas (RNG) and associated bioproducts through the anaerobic digestion (AD) of diverse feedstocks

Situation	Inputs	Activities and Outputs
Global human population is expected to reach 10 billion by 2050 • The dominant agricultural systems that support 7.6 billion people today are challenged by diminishing land and water resources, climate variability, threats of disease and pest outbreaks, and challenges to human health and well-being • A convergence of science, technology and policy is needed to solve these challenges • Any new systems approach will need to significantly improve the supply of affordable, safe, nutritious, and accessible agricultural products, while fostering economic development and rural prosperity in America	**Team:** Scientists, engineers, industry leaders, extension specialists, and educators • Institutions in 4 states IA (Iowa State U., USDA ARS), PA (Penn State U.), MO (Roeslein Alternative Energy), and OH (FDC Enterprises) • Farmer and industry cooperators • Data and experimental results from existing projects **Institutional support:** Research infrastructure: equipment, labs, and farmland • Teaching, Extension, communications staff and offices • Entrepreneurial programs • Collaboration, data management, and publication platforms **External:** Evaluator • Advisory board • Stakeholder and NGO input • Farmer and industry expertise and investments • Federal/state technical assistance • USDA NIFA SAS CAP funding	**Research:** 1 biobased value chain with 1 commercial digester, 3 field experiments, 10 partner commercial farms, 3 models improved/expanded • 1 project-wide data management system and data from: ~7 biobased utilization pathway simulations, ~10 bioproduct intensification lab experiments, ~5 pilot digester experiments, commercial digester tests, 1000s of cropping systems simulations, 3 field experiments, 10 farms, 6 focus groups, 50 interviews, 4 workshops • Stakeholder evaluation of 2-4 alternative value chain scenarios • Documented knowledge gains, gaps, and policy options through >20 publications, 50 farm reports • **Extension:** 5 Digester Days • 10 webinars • 3 short courses • 3 business case studies, market analyses • 1 updated online course • 50 individual farmer meetings • 2 peer-to-peer farmer learning networks • 10 farm demonstrations • 8 listening sessions • 16 farm field days • 8 workshops • 4 leadership circle meetings • 56 presentations • **Education:** 2 expanded high/middle school training programs • 8 new educational modules • 2 expanded undergraduate entrepreneurial training programs • 60 undergraduate internships • 720 student pro-jects • **Evaluation:** Data from web analytics, event participation, 50 farmer interviews, pre/post assessments of 59 teachers and 7,250 students, 250 interviews and 400 survey of stakeholders • 5 reports **Participants:** Entrepreneurs/businesses involved in rural economic development and sustainability • Farmers, farm owners, farm advisors, conservation professionals, agricultural businesses • Thought, business, and policy leaders • High/middle school teachers and students • Undergraduates

LOGIC MODEL FOR INTEGRATED PROGRAM

Outcomes *Short Term*	*Medium Term*	*Long Term*
Anaerobic digestion (AD) of herbaceous feedstocks with manure is a proven strategy for (1) producing bioproducts with improved functionality, increased revenues, and reduced cost over incumbent products; (2) producing beneficial ecosystem services, including improved water quality, improved life cycle emissions, and nutrient use reduction; and (3) alleviating technical, economic, social, and behavioral barriers leading to bioeconomic devel-opment • Increased bioeconomic content skill sets/ knowledge among agricultural, energy, and ecosystem service entrepreneurs; farmers, farm owners, farm advisors, conservation professionals, agricultural businesses; thought, business, and policy leaders; high/middle school teachers/students; undergraduates • Increased biomass conversion efficiencies • Increased success of existing on-farm digesters • Increase in the number of farmers in focal regions using subfield management decision tools and practices • Increase in crop productivity/farm profitability	Science-based decision making about the bioeconomy by farmers, farm owners, entrepreneurs, industries, teachers, students, and societal stakeholders that improves their lives and livelihoods • New investments and policies to remove key technical, social, behavioral, and economic barriers to implementing the new value chain • Increased number of on-farm digesters • Increased number of famers in focal regions growing biomass crops • Innovation to widely expand the number of new value-added biobased products from the value chain • Expansion of existing and/or development of new businesses and value-added agricultural markets • Creation of new, permanent, technical rural jobs as a result of project	Improved human-health, economic prosperity, energy security, and ecosystem resources in the Upper Midwest and Mid-Atlantic regions •A society more educated about and supporting an expanded bioeconomy • The expansion of the value chain to other regions • A national supply of affordable, safe, nutritious, and accessible agricultural products • A prosperous rural America • A model for what can be done elsewhere

Assumptions:
The AD of herbaceous biomass with manure will improve the productivity, profitability, and sustainability of agricultural systems • Intensification and modularization will advance the AD of distributed herbaceous feedstocks and increase profitability of biobased supply chains • Coordinated research, education, and extension will accelerate the transformation to more productive, profitable, sustainable agricultural systems

External Factors:
Stakeholders willingness to participate in new biobased value chain • Fluctuating market support for row crops (i.e., trade restrictions) • Major changes in federal regulations dis-/incentivizing production of biorenewables • Major changes to California’s Low Carbon Fuel Standard • Accelerated changes in weather impede/prevent economically viable crop production

GRANT RECIPIENTS

IOWA STATE UNIVERSITY

THE PENNSYLVANIA STATE UNIVERSITY

ROESLEIN ALTERNATIVE ENERGY

FDCE INC.

USDA AGRICULTURAL RESEARCH SERVICE
NATIONAL LAB FOR AGRICULTURE AND THE ENVIRONMENT