## Introduction to Carbon Negative Energy

Reducing carbon dioxide ($CO_2$) emissions may not be enough to curb global warming according to the Intergovernmental Panel on Climate Change. The solution will also require carbon-negative technologies that actually remove large amounts of $CO_2$ from the atmosphere. The concentration of $CO_2$ in the atmosphere has risen by roughly 70% since the industrial revolution, causing a 0.85$^{o}$C increase in global mean temperature. Currently, the energy sector is a major contributor to the increasing atmospheric $CO_2$. A growing global population and increased energy demand will cause an additional rise in atmospheric $CO_2$ unless we seek alternative energy resources. Renewables such as solar, wind, hydro, bioenergy, and direct emissions reductions technologies such as carbon capture and storage (CCS) could help curb $CO_2$ emissions. To augment these, technologies exist that remove atmospheric $CO_2$ and can potentially keep it out of the atmosphere. Among these are bioenergy with carbon capture and storage, direct air capture, and biochar. These technologies have benefits and downsides and vary drastically in predicted cost.

In the U.S., transportation is the second biggest human caused contributor to the carbon dioxide ($CO_2$) emissions, accounting for close to 30% of the total. Biofuels done in the right way could contribute to a net reduction in emissions from this sector. Well-managed biofuels crops could lead to increased soil carbon and coupled with carbon dioxide storage from the conversion process could lead to overall net negative $CO_2$ emission in the lifecycle of the biofuel.

GCEP currently funds two projects in this area.

One is led by Professors Laird and Brown and a consortium at Iowa State University in collaboration with Professor Zilberman and UC Berkeley. This project entitled “The Pyrolysis-Bioenergy-Biochar Pathway to Carbon-Negative Energy”, aims to investigate the potential for an integrated pyrolysis-bioenergy-biochar industry to economically and sustainably produce carbon-negative renewable energy. During the first year of this project techno-economic analysis of two scenarios for deployment of the pyrolysis-bioenergy-biochar industry have been conducted. For the biochar & biofuel scenario, bio-oil is hydro-treated and then refined to produce both gasoline and diesel. In the biochar & bio-power scenario, bio-oil is mixed with crushed coal and then burned in existing coal-fired power plants to produce electricity. In addition this project is developing a biochar model that provides for the first time a means of systematically investigating complex soil-biochar-crop-climate systems, and critically a means of estimating the agronomic and environmental impacts of soil biochar applications for specific regions and agronomic systems. This capability is critical for determining the local value of the biochar co-product. Major accomplishments during the first two years of this project include the design and development of a biochar module within the Agricultural Production Systems sIMulator (APSIM), a widely used and publically available cropping systems model. The APSIM Biochar Model provides for the first time a means of systematically investigating complex soil-biochar-crop-climate-management interactions, and critically a means of estimating the agronomic and environmental impacts of soil biochar applications. Much effort during the second year of the project was focused on quantifying and developing a mechanistic understanding of how biochar influences nitrogen dynamics and bioavailability in soil environments. Sorption of nitrate and ammonium by biochar were shown to be strongly dependent on pH and peak pyrolysis production temperature. Focus was also placed on developing a rapid method for determining the size and properties of the labile and recalcitrant biochar fractions, as these are needed to accurately parameterize "biochar quality" within the APSIM Biochar Model. Substantial progress was made in calibrating and validating the APSIM Biochar Model using literature data from globally diverse field and laboratory experiments. Techno-economic analysis has used to determine the minimum fuel selling price (MFSP) and lifecycle ghg emissions for a 1000 dry ton per day fast pyrolysis plant. The ash content of the biomass feedstock had a significant effect on MFSP and ghg emissions, indicating a trade-off between economic and environmental benefits based on feedstock selection. The techno-economic analysis also demonstrated that the Pyrolysis-Bioenergy-Biochar Pathway has the potential to produce carbon negative energy products even when indirect land use and synergistic agronomic and environmental effects of soil biochar applications are discounted. This project has already led to sixteen peer-reviewed publications, four in press, and an additional eight in preparation.

The second project led by Professors Larson and Williams at Princeton University and Professor Tilman at the University of Minnesota is entitled "Sustainable Transportation Energy with Net Negative Carbon Emissions: An Integrated Ecological and Engineering Systems Analysis". The Princeton and Minnesota researchers are collaborating on the science and technology of alternative negative GHG-emitting biomass energy systems that might be deployed commercially before mid-century to help meet U.S. transportation energy needs. One of the goals is to understand better system-wide implications of two mechanisms for achieving negative emissions: geologic storage of $CO_2$ captured during feedstock conversion (CCS) and storage of photosynthetic carbon in biomass roots and associated soil. The fundamental science being advanced is a new and comprehensive understanding of the ecological dynamics and root/soil (R/S) carbon storage potential for perennial grasses grown on the significant acres in the U.S. of degraded soils ill-suited for conventional agriculture.

Over the last few gorwong seasons the Minnesota researchers have collected extensive field data from three to quantify the potential for biomass energy production and concomitant R/S carbon storage. They have completed partial analysis of the data collected thus far from all three experiments and done preliminary life-cycle analysis on the carbon implications of fertilization and irrigation. They found that the soil organic carbon in high-diversity (16 plant species) prairie grassland had continued to increase since planting over two decades ago and at a much higher rate than in monoculture grassland. The aboveground biomass yield in high-diversity (16 plant species) prairie grassland was also much higher than in monoculture grassland when neither nitrogen nor irrigation were applied. For nitrogen application, moderate amounts of application (70 kg ha-1 yr-1) increased aboveground biomass yield for both high-diversity (32 plant species) and low-diversity (<5 plant species) prairies. However, biomass yield decreases with larger nitrogen application (140 kg ha-1 yr-1) for high-diversity (32 plant species) prairies, partly because excessive nitrogen leads to biodiversity loss (fewer number of species). The Energy Systems Analysis Group (ESAG) at Princeton continued its technical performance, ghg emissions economic viability assessments of prospective bioenergy with carbon capture and storage systems for producing ground or air transportation fuels that can be "splash-blend" replacements for petroleum-derived fuels. In comparing gasification and hydropyrolysis assessments, the latter pathway appears more favourable, with higher liquid yield, lower capital-investment intensity, and lower production cost. The second year's effort also saw the start of work on processes involving decomposition of biomass to simple sugars followed by either biological or catalytic sugar conversion to gasoline-like and diesel-like fuels. So far, this work has led to four peer-reviewed publications.