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 emissions in the lifecycle of the biofuel.

GCEP has two projects coming to an end in this area.

One project is led by Professors Laird and Brown, a consortium at Iowa State University, and is in collaboration with Professor Zilberman at UC Berkeley. This project entitled "The Pyrolysis-Bioenergy-Biochar Pathway to Carbon-Negative Energy", aimed to investigate the potential for an integrated pyrolysis-bioenergy-biochar industry to economically and sustainably produce carbon-negative renewable energy. In this work the researchers developed, parameterized, and validated a biochar module for the *Agricultural Production Systems sIMulator* (APSIM). They used techno-economic analysis to assess the economic performance of pyrolysis plants producing bioenergy and biochar co-products and used life cycle assessments to determine the net GHG emissions from an integrated pyrolysis-bioenergy-biochar production facility. The public and private benefits accrued from integrating biochar into pyrolysis-based bioenergy production systems for three case studies were quantified. Carbon credits for indirect land use avoidance and compare system production costs were estimated.

Through these approaches the researchers successfully advanced basic understanding of the impacts of biochar on agroecosystems; assessed the technical and economic viability of an integrated pyrolysis-bioenergy-biochar industry in the Upper Mississippi River Basin (UMRB), California, and U.S. Southeast; assessed regional and global impacts of an integrated pyrolysis-bioenergy-biochar industry on indirect land use and net GHG emissions; and have built a foundation for the development of a vanguard economicallyviable carbon-negative integrated pyrolysis-bioenergy-biochar industry. This project has been very productive and has led to 31 peer-reviewed publications and 5 additionally in preparation or under review. Five PhD theses were also produced from this work.

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".

This project assessed alternative bioenergy production and conversion systems with carbon capture and storage (BECCS) that might begin to be deployed commercially beginning in the relatively near term to help meet U.S. mid-century carbon-mitigation goals and transportation energy needs. The system-wide implications of two mechanisms for achieving negative greenhouse gas (GHG) emissions were assessed: geologic storage of CO_2 captured during feedstock conversion (CCS) and storage of photosynthetic carbon in roots/soil (R/S) during biomass production. The work was a collaboration between researchers at the University of Minnesota (UMN) and Princeton University (PU), with colleagues from Colorado State University (CSU) joining in the final year of the project.

Field experiments at UMN shed light on the ecological dynamics and R/S carbon storage potential of perennial grasses grown on agriculturally-degraded soils, of which there may be as many as 45 million hectares across the U.S. CSU researchers undertook high-resolution, national-scale modeling to estimate the potential for perennial grass production on such areas, including R/S carbon uptake. PU undertook techno-economic analysis of multiple bioenergy conversion technology pathways to understand comparative costs and benefits. PU integrated their findings with results from UMN and CSU to develop a national-scale assessment of the potential for BECCS systems to help meet mid-century U.S. transportation energy needs and carbon mitigation goals.

The work by researchers at Colorado State highlights inter- and intra-regional variability in the net GHG balance of switchgrass cultivation. This variability provides a basis and opportunity for policy design to support regionally-appropriate land uses and landscape optimization. The land areas most likely to achieve positive environmental outcomes should be the focus of production practices.

PU researchers developed self-consistent techno-economic assessments of alternative processes for converting lignocellulosic biomass into liquid transportation fuels fungible with petroleum-derived fuels. The pathways included gasification- and hydropyrolysis-based systems, as well as microbial and catalytic conversion of sugars generated by enzymatic hydrolysis of biomass