Summary of

CRC Workshop on
Life Cycle Analysis of Transportation Fuels

Argonne National Laboratory
October 24-26, 2017

A. Introduction

On October 24-26, 2017, the Coordinating Research Council (CRC) hosted a workshop at Argonne National Laboratory near Chicago, Illinois, which focused on technical issues associated with life cycle analysis (LCA) of transportation fuels, with an emphasis on biofuels. The workshop was co-sponsored by API, Argonne National Laboratory, California Air Resources Board, Canadian Fuels Association, CONCAWE, National Biodiesel Board, Renewable Fuels Association, US Department of Agriculture, the University of Michigan Energy Institute, and the Union of Concerned Scientists. This was the fifth in a series of bi-annual LCA Workshops organized by CRC. The four specified goals of this Workshop were very similar to those of previous Workshops:

- Outline technical needs arising out of policy actions and the ability of LCA to meet those needs.
- Identify research results and activities that have come to light in the past two years that have helped to close data gaps previously outlined as outstanding issues.
- Identify data gaps, areas of uncertainties, validation/verification, model transparency, and data quality issues.
- Establish priorities for directed research to narrow knowledge gaps and gather experts' opinions on where scarce research dollars would best be spent.

The workshop had 105 total attendees, including 20 international attendees. Compared to previous Workshops, there were more attendees from Canada, and fewer from the EU. Representatives were present from government bodies (including National Laboratories), industry, academia, and non-governmental organizations (NGOs). Fifteen technical presentations were given, organized into five Technical Sessions. Included in these sessions were three moderated panel discussions.

This Workshop Summary report highlights the topics discussed in each session as well as the knowledge gaps identified by the speakers, the session chairs, and through interaction with the workshop participants. The abstracts and workshop presentations are available on the CRC website provided here.

This report is organized into the following sections: (A) Introduction, (B) Overall Workshop Highlights, (C) Session Summaries, Information Gaps and Data Needs, and (D) Highlights and Learnings from Individual Presentations. A glossary of terms used during the Workshop is included as an appendix.

B. Overall Workshop Highlights

Given below are brief overall impressions and highlights from the LCA Workshop. This list is not comprehensive, but attempts to capture the most important observations, significant take-home messages, and common themes that emerged from the information presented.

- Application of LCA to define carbon intensity (CI) of transportation fuels has become more accepted, as regulations have moved forward and affected parties are focused on determining how to most effectively comply. Nevertheless, it is recognized that some of the longstanding problems – such as data quality and model uncertainty – continue to exist, and are the subject of on-going work. At the same time, some researchers indicated that deriving CI values for biofuels within the context of the real world and its complex dynamics represents an intractable problem.

- The issue of indirect land use change (ILUC) remains controversial – both in principle and in application. Recent revisions to ILUC models have utilized updated global economic databases and more detailed characterization of land use change (LUC) locations and types. These updates, as utilized within the GTAP modeling approach, have reduced the estimated ILUC effect on the carbon intensity (CI) of biofuels, although large uncertainties remain.

- Some regulatory applications of LCA have become clearer and more firmly entrenched. In recent years, the U.S. EPA has not significantly changed its methodology or models for assessing the GHG reduction potential of biofuels, but continues to apply them to a wider range of fuel pathways. The California Air Resources Board (CARB) has not changed its fundamental LCA methodology, but has updated the models it utilizes, including adopting an updated agro-economic model and underlying databases used to determine ILUC and its contribution to a fuel's CI value.

- There is general consensus that our understanding of LUC has improved dramatically over the past decade. This has been driven both by improved observational methodologies – such as remote sensing – and by improved databases. During recent years of biofuel expansion, there has been less agricultural extensification and more intensification than was represented in previously-used models. Proper distinction between intensification and extensification is necessary for reliable assessment of LUC and its impact on the CI of biofuels. The practice of double-cropping is now recognized as an important factor that has significant spatial variability and must be handled correctly when assessing LUC. However, a lack of reliable data on planted crop areas and double cropping is an ongoing impediment to such modeling.

- Most commercial biofuel feedstocks in the U.S. are co-produced with protein for livestock feed. The role of protein demand should not be underestimated when evaluating trends on the agricultural landscape.

- Common biodiesel feedstocks include both edible and inedible oils, some of which are also used within the food market. Because one oil can be substituted for another, changes in market demand for biodiesel can influence the demand of several vegetable oil commodities. Empirical modeling utilizing instrumental variables has been investigated as a way to tease-out causality when analyzing data with correlation effects. This is important to address the concern that expanding the use of biodiesel could increase demand for palm oil, which is associated with very high GHG emissions.

- When determining ILUC and its impact on a biofuel's CI value, current regulatory modeling methodologies utilize a static approach, whereby a single biofuel shock disrupts the existing agro-economic system. However, several speakers discussed the use of dynamic, integrated assessment models (IAMs), believing that they are better able to represent the incremental impacts and feedbacks of policy options in the real world.

- The most commonly used regulatory models for LCA of biofuels have numerous methodological differences, due to their different origins, purposes, and underlying databases. Differing goals between regional and national policies make it unlikely that a single, unified model will be developed.

- Continued advancements are being made in understanding and modeling of how changing cropping patterns – including increased production of biofuel crops – affect soil organic carbon (SOC) levels. In addition, SOC impacts of land management activities – such as corn stover removal, application of manure, and introduction of winter cover crops – are becoming better understood.

- In the U.S. Midwest, SOC levels in croplands have increased substantially over the past several decades. This has been driven largely by reduced tillage practices and other land management improvements. Because currently used models tend to under-predict these SOC increases, additional research is needed in this area.

- The DayCent bio-geochemical model is used as the foundation for determining national-level GHG fluxes on an annual basis. Through this process, it has been shown that U.S. croplands in total constitute a modest GHG sink, with an annual sequestration of approximately 27 Tg CO_{2eq}.

- System dynamics (SD) modeling approaches are beginning to be used in evaluating the complex interactions between biofuel policies and broader economic systems, and how these interactions change with time. From a conceptual standpoint, such SD approaches focus more on carbon dynamics as compared to traditional economic modeling approaches involving single biofuel shocks and static economic systems.

- The long-standing assumption of carbon neutrality of corn ethanol is now being explored. Based upon stock and flow carbon accounting methods, as well as global dynamic modeling utilizing an Anticipated Baseline Approach (ABA), speakers indicated that the assumption of complete carbon neutrality is not correct. This is important, as any reduction in carbon neutrality translates to a higher CI value for corn ethanol.

- Cradle-to-grave analysis of a matrix of vehicle/fuel options predicts substantial GHG reductions in the future (2030) due to increased vehicle efficiency and use of renewable energy sources. In most cases, the levelized cost of driving (LCD) is dominated by the vehicle lifetime cost component, not the fuel cost. With current technologies, LCD and cost of avoided GHG emissions are lowest for conventional vehicle/fuel cases, while advanced technologies – such as battery electric and fuel cell vehicles – become more attractive in the future.

- Emissions of methane occur at numerous locations throughout the natural gas (NG) production and distribution value chain. Accurate quantification of these emissions is important to identify areas where additional controls could be applied, and to determine the life-cycle GHG benefits of

NG applications in comparison with other fuels. While significant improvements have been made, discrepancies remain between top-down and bottom-up inventory assessments.

- In both Europe and the U.S., new LCA methodologies are being developed to assess GHG benefits of novel transportation fuels. In the EU, fuels derived from non-biologic feedstocks and waste materials are being considered. In California, CARB is now considering how to apply LCA methodologies to determine CI values of fuels that are produced by co-processing of fossil and biogenic feedstocks in petroleum refinery process units.

C. Session Summaries, Information Gaps and Data Needs

Session 1: Retrospective Analysis and Implications for LCA

Session 1 focused on understanding what can be learned from recent historical data regarding land use change (LUC), and how this information influences LCA studies of biofuels and their resultant carbon intensity (CI) values. It is clear that over the past 10-15 years, crop intensification in the U.S. has dominated over crop extensification, whereas both intensification and extensification have occurred in other locations. Updates to global economic models are being made to provide better representation of agricultural intensification vs. extensification – along with many other improvements. The practice of double-cropping has important impacts on harvested area and total crop production. The agro-economic models being used are improving in their ability to represent double-cropping and its spatial variability. Global dietary trends show increasing demand for total calories and increased protein. These trends influence the supply and cost of basic food/feed commodities, which in turn influence decisions regarding the type, location and amount of crops that are grown, and the inter-relationships among food and fuel production from the land. In this way, biofuels are inextricably linked to food/feed markets. The ready substitution of one vegetable oil for another within the food market raises the concern that increased demand for biodiesel fuel could increase production of palm oil, which is associated with high GHG emissions.

Session 2: LCA Methodology

Session 2 addressed recent methodological developments regarding LCA modeling, and highlighted remaining issues. One new approach utilizes fundamental thermodynamic data to model chemical processes and products at a molecular level, thereby enabling assessment of process modifications to optimize life-cycle energy requirements and GHG impacts. Dynamic integrated assessment models (IAMs) are being more widely investigated to assess a broader range of impacts from biofuel policy options. Such consequential life cycle assessment (CLCA) approaches examine not only GHG impacts of specific policies, but also impacts on primary energy supplies, agricultural practices, commodity prices, and other economic activities. In an example that was presented, an IAM model called GCAM was used to show that changes over time of GHG emissions, rebound effects, and radiative forcing were highly sensitive to model input assumptions. Significant methodological differences continue to exist among the LCA models most commonly used in regulatory assessments of CI values for biofuels. Due to differences in regulatory purposes, geographic scope, and data limitations, it is unlikely that a single, unified LCA model can be developed. However, it is desirable for each regulatory jurisdiction to update whatever methodology is being used to incorporate the most relevant and reliable data inputs.

Session 3: Soil Organic Carbon

Session 3 focused on issues related to soil organic carbon (SOC) trends, estimation methods, and impacts on CI values of biofuels. Using the GREET model, along with the Carbon Calculator for Land Use change for Biofuels (CCLUB) module, changes in SOC resulting from specific cropping practices or land transitions can be estimated. Initial modeling results indicate that transitioning land from cropland-pasture to corn cropping has little effect on SOC levels in most locations. Also, depending upon the type of land management practices being employed, the beneficial impacts of increasing SOC can contribute to very low (and even negative) values for CI of stover-derived ethanol. When left on the fields, crop residues provide numerous benefits with respect to erosion control, improving SOC levels, and overall soil health. Therefore, consideration is now being given to determining the optimum balance between residue removal for biofuels and residue retention for soil benefits. Based upon extensive soil sampling data, it is clear that SOC levels in croplands are increasing throughout most of the U.S. Midwest. However, models used to estimate SOC generally under-predict the extent of this increase, by assuming constant SOC over time. The DayCent ecosystem model is used to estimate GHG fluxes from soils. When applied on a national scale, and combined with other land use data sources, it is used to estimate total annual GHG flux from U.S. cropland. Such information is used to satisfy national GHG reporting requirements and to support analysis of mitigation policies.

Session 4: Alternative Carbon Modeling Methods

Session 4 addressed alternative methods of carbon modeling for biofuels, as compared to conventional LCA approaches. One important consideration is the static nature of current economic modeling approaches of biofuel scenarios, which consider how a given agro-economic system responds to a single shock of biofuel demand. As an alternative, system dynamic (SD) approaches utilize stock and flow concepts to track carbon mass, and include feedback loops to represent constantly evolving changes in economic systems that occur in a dynamic world. In some respects, SD approaches are better suited for evaluating real-world impacts of biofuel policy options than are traditional LCA approaches. It may be useful to explore ways in which SD and LCA approaches could effectively complement each other. The concept of carbon neutrality of CO_2 emissions associated with the production and use of corn ethanol is now being examined in more detail. Typically, LCA assessments have assumed that biogenic CO_2 emissions from the fermentation process to produce ethanol and from fuel combustion in the vehicle can be ignored, because these processes are merely recycling carbon that was recently extracted from the atmosphere. However, stock and flow analyses that include an Annual Basis Accounting (ABC) of carbon mass suggests that (over a multi-year period) the amount of biogenic carbon emitted to the atmosphere exceeds the amount that is taken up by the biosphere. In another approach, a global dynamic economic model was used to assess the impacts of biofuels policies over time. Such modeling enables evaluation of a realistic base case and a test case, and the difference between the two, all of which change over time. Results obtained using this Anticipated Baseline Approach (ABA), with the specific scenarios being modeled, also suggest that carbon neutrality is less than 100%. In the traditional LCA approach used for biofuels, any reduction in carbon neutrality translates into a higher CI value.

Session 5: LCA of Emerging Technologies

Session 5 focused on LCA as applied to novel or emerging technologies. In one example, a range of vehicle and fuel options was modeled on a cradle-to-grave (C2G) basis to estimate relative life-cycle GHG emissions, levelized costs of driving (LCD), and costs of GHG reduction. Results showed that in current year scenarios (2015), LCD and costs of GHG reduction are lowest for conventional vehicle/fuel cases, while in future scenarios (2030), more advanced technologies – such as battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) become more competitive. Another study focused on GHG emissions (primarily methane) associated with extraction, processing, transmission, and distribution of natural gas. In such assessments, it is important to carefully define the system boundaries – both spatially and temporally. Discrepancies between top-down and bottom-up methane inventories persist, and are attributed to lack of understanding and high uncertainties of certain emissions sources. Under requirements of the EC's Fuel Quality Directive (FQD), efforts are underway to establish GHG reduction values for novel transportation fuels derived from non-biological feedstocks and from waste materials. To date, the GHG savings have been evaluated from four novel pathways, with the results varying substantially among the different EU Member States – largely due to differences in carbon intensity of the various electricity grids. In California, methodologies are being developed to define CI values of fuels that are produced through co-processing of biogenic and fossil feedstocks in conventional petroleum refinery process units. Due to differences in system boundaries and external energy inputs, these CI-determining methodologies must be customized to the specific processing unit being used.

D. Highlights and Learnings from Individual Presentations

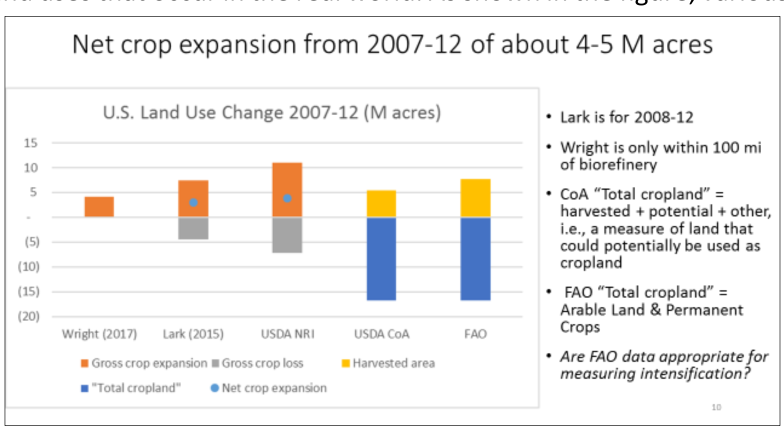
Session 1: Retrospective Analysis and Implications for LCA

Chairpersons: Aaron Levy (US EPA) and Stephanie Searle (ICCT)

Session 1 consisted of four presentations that provided overviews of historical trend data regarding agricultural productivity, land use change (LUC), and trends in oilseed markets. Aaron Levy of EPA set the stage for further discussion throughout the Workshop by reviewing agricultural and biofuel trends over roughly the past 15 years, in both the U.S. and globally. Farzad Taheripour of Purdue University discussed LUC trends associated with intensification and extensification of biofuel feedstocks, and how this information is used in models to estimate GHG emissions attributable to the biofuels. Don Scott of the National Biodiesel Board (NBB) reviewed broad trends in nutrition and diet, and how this relates to biofuel feedstocks. Finally, Stephanie Searle of the International Council on Clean Transportation (ICCT) discussed market trends for various vegetable oils, and how the substitution of one oil for another can influence LUC and affect the GHG impacts of biofuels.

Aaron Levy (US EPA) discussed changes in land use that occurred during the recent period of rapid biofuels ramp-up (2000-2014), as land use change is a key contributor to the lifecycle GHG emissions associated with biofuels. The trends discussed by Levy were all derived from publicly-available data sources – primarily from the U.N. Food and Agriculture Organization (FAO), the USDA, and the U.S. Energy Information Administration (EIA). It was pointed out that many other sources of data are available, and that in trend analysis of this type, it is critical to define clearly what information sources are being used. It was also emphasized that by themselves, assessments of historical agricultural and land use trends do not provide conclusions about how much of the observed impacts are attributable to biofuels.

In the U.S., biofuels production has risen by approximately 1.0 billion gallons/year (bg/y) over the past 16 years. About 90% of this biofuel is ethanol, produced from corn starch. Biodiesel comprises most of the remaining biofuel, with approximately 50% of this being produced from soy oil. Despite these large increases, total biofuels still comprise only 7% of U.S. liquid transportation fuels (in 2016). Total U.S. cropland area has increased by only about 1% over this time period. However, crop intensification has been much greater, with yield (tons/acre) and total production (tons) increasing by 16% and 18%, respectively. Obtaining reliable estimates of cropland expansion is difficult, due to different definitions being used and constant switching of land uses that occur in the real world. As shown in the figure, various assessments show that net crop expansion in the U.S. between 2007 and 2012 was 4-5 million acres. Most of this expansion is believed to have come from conversion of pasture and reversion of Conservation Reserve Program (CRP) lands. Levy also showed that gains in overall corn and soybean production allowed corn and soybean exports to hold steady as ethanol and biodiesel production increased.



Globally, biofuels production has risen by about 2 bg/y since 2000 – double the rate within the U.S. alone. At the same time, global cropland expansion, crop yield, and total crop production increased by 17%, 21%, and 42%, respectively. Cropland expansion coincided with loss of pasture land and forested land, with the relative amounts of these land losses varying regionally. Forest loss was greatest in Africa, Brazil, and the rest of Latin America. It is important to note that over this same time period, global population increased 16% and per capita GDP almost doubled. Levy emphasized that to gain a better understanding of the linkages between biofuels and land use requires improved data. In particular, planted area is key for assessing land use change and the extent of intensification/extensification. At present, FAO data include arable land and harvested area, but not planted area, which raises questions about any inference of multi-cropping or other forms of intensification from these data.

Farzad Taheripour (Purdue Univ.) described the evolution and use of computable general equilibrium (CGE) economic models to estimate induced (or indirect) land use change (ILUC) arising from biofuel production shocks. One of the best known such models, called GTAP-BIO, is currently used by the California Air Resources Board (CARB) in determining CI values for biofuels in the California Low Carbon Fuels Standard (LCFS) program. Predicted changes in land use by country and agro-economic zone (AEZ) are coupled with information about carbon stocks in each location to predict changes in ILUC GHG emissions, and hence CI, resulting from a defined biofuel shock.

Taheripour explained that both the GTAP model and its associated global economic database have evolved over time. Recently, the economic database has been updated from one representing the global economy in 2004 to one that represents the global economy in 2011. Major changes to the GTAP-BIO model have been made to better represent the extent of crop intensification and extensification that has actually been observed in recent years. Intensification factors were added to GTAP-BIO based on "tuning" of FAO land use data. In general, there is more intensification and less extensification than was previously represented in GTAP-BIO. Simulations using the new GTAP-BIO model generally show lower ILUC globally for a given biofuel shock, and thus lower associated GHG emissions.

Crop yield is one factor that significantly affects ILUC results. Within GTAP, crop yield is represented by a term called Crop Yield Index, which varies spatially and temporally. From 2003 to 2013, crop yield index increased in the US, EU, Brazil, and China; but remained constant or decreased in other locations. It is also important to consider differences between total cropland area and harvested area. In the U.S., and many other countries, there is considerably more total cropland area than harvested area. In China, however, the opposite is true, due to extensive use of double-cropping. The GTAP-BIO model has been improved to better account for the occurrence of double-cropping, and its spatial variation. The updated model shows large variations in cropland intensification due to double-cropping from one region to another.

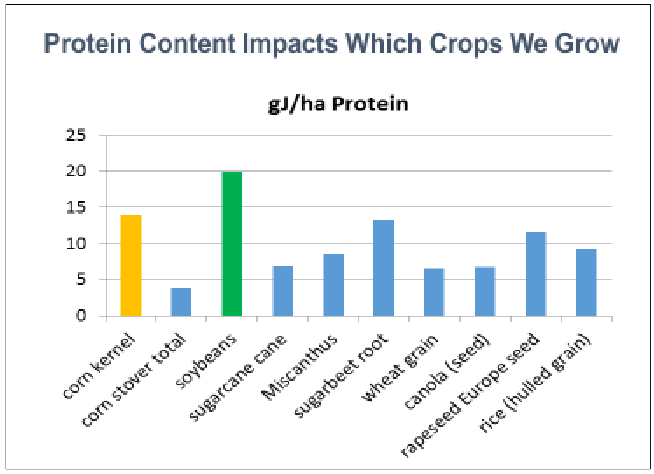
A number of model simulations were conducted to investigate the effects on ILUC results of both updating the GTAP-BIO model and of changing from 2004 to 2011 economic databases. The ILUC CI results (in units of g CO_2eq/MJ) are shown in the figure. For all the fuels investigated, CI values were reduced when using the new GTAP-BIO model, and the reductions were larger when using the newer database.

ILUC Emissions – Model and database Comparison

2004 database	Old Model	New Model	% Reduction
US corn ethanol	13.4	8.7	-35.1
Brazilian sugarcane ethanol	5.68	4.7	-17.3
US soybean biodiesel	21.62	16.9	-22.8
EU rapeseed biodiesel	26.55	15.7	-40.9

2011 database	Old Model	New Model	% Reduction
US corn ethanol	23.3	12.0	-48.5
Brazilian sugarcane ethanol	13.0	3.2	-75.3
US soybean biodiesel	25.5	18.3	-28.2
EU rapeseed biodiesel	23.7	13.7	-42.1

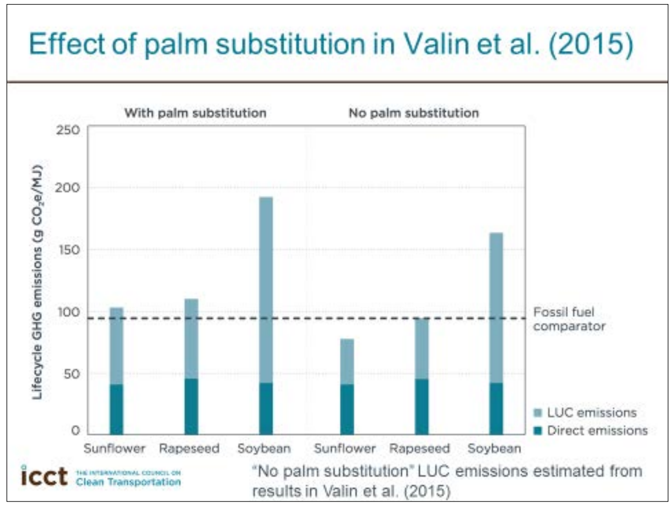
Don Scott [National Biodiesel Board (NBB)] presented information regarding dietary demands for protein, carbohydrates, and fats – along with the production and use of crops to satisfy these demands. Protein is the limiting factor in our food supply, but the most efficient protein crops produce more fats and carbohydrates than needed for food or feed. Therefore, growing and harvesting the required amount of protein results in an over-supply of fats and carbohydrates. Globally, overall per-capita calorie consumption is increasing, with fat consumption increasing faster than protein consumption. On a kcal basis, protein is more expensive than either fats or carbohydrates. As shown in the figure, protein production per acre is higher for soybeans than for any other major crop. Production of biofuels provides useful outlets for the excess oils produced along with this protein. A major function of the livestock industry is to convert plants to animal protein for human consumption. With current U.S. meat consumption trends towards reduced beef and increased poultry, this allows for more efficient conversion to meat, and enables sufficient production to occur with overall shrinking amounts of farmland.



While biodiesel prices correlate in time to soybean oil prices, Granger Causality has shown that changes in the RFS biodiesel mandates have not had any impact on soybean oil prices. This is because the amount of soybean oil is controlled by the amount of soybean crush, which is driven by the soy meal demand in the food/feed markets. Due to increased demand for protein, vegetable oil supplies have grown faster than biodiesel production. Thus, Scott argued that the inextricable linkages between biodiesel and the food/feed market needs to be considered when assessing renewable fuel policies, such as the RFS, including the ILUC impacts.

Stephanie Searle (ICCT) discussed the linkages among different vegetable oils in the US and EU, and the potential effects this has had upon ILUC GHG emissions associated with biofuels. This topic is of concern because substitution by palm oil could increase the demand for additional palm production. If such production occurs on peat soils, large emissions of GHGs would result. Due to their similarities in food usage, one vegetable oil is commonly substituted for another, based upon cost and availability. To illustrate this behavior, Searle presented trend data showing that the prices of sunflower oil, rapeseed oil, soybean oil, and palm oil closely tracked together from 2008 to the present. In the U.S., at the same time increasing amounts of soy oil were being used to produce biodiesel, imports of palm oil increased for use in the food markets. This trend towards increased palm oil may be reinforced by policies now coming into effect that restrict the use of trans fats in foods, as low trans fat palm oil can be used to replace high trans fat partially hydrogenated soy oil. In Europe, the situation is different, as palm oil has been used directly as a biofuel feedstock, and palm imports have increased along with total biodiesel production. Imports of palm oil into the EU have also risen with increased price of rapeseed oil – the dominant biodiesel feedstock in the EU. Searle concluded that vegetable oil substitution is an important factor that must be represented accurately during ILUC modeling. It is possible that with future high demand for soy- and rapeseed-derived biodiesel, palm oil demand could also increase, resulting in adverse GHG impacts.

To further investigate the supply and demand causalities of vegetable oils, and their substitutions for each other, ICCT commissioned an economic study at the University of Foggia, Italy. An empirical model was constructed using instrumental variables (IV) of past biofuel production shocks and commodity consumption to identify causal relationships. Results confirmed that the vegetable oil markets are linked, at least to some degree, in both the US and EU. In the US, the price of soy oil was found to have a weak effect on soy oil supply, but it strongly drove the amount of palm oil imports. In the EU, the price of rapeseed oil had a strong effect on both the supply of this oil and the amount of palm oil imported. The extent to which vegetable oil substitution is reflected in ILUC modeling changes the predicted GHG impacts of the fuels. This is illustrated in the figure, which shows carbon intensity values determined by GLOBIOM modeling scenarios for biodiesel produced in the EU from three feedstocks with palm oil substitution, compared to scenarios without substitution. When allowing for this substitution, the calculated CI values are substantially greater for all feedstocks.



Panel Discussion [Moderated by Jennifer Dunn, Argonne National Laboratory, (ANL)]

Dunn began the panel discussion by asking whether we now have general agreement regarding historical LUC trends. Levy replied that while we have a better understanding of the amount of intensification vs. extensification, we don't fully understand the reasons for the LUC. In addition, uncertainties regarding LUC amounts and locations are quite high in many places outside the U.S. Taheripour mentioned that additional information about cropland use by AEZ is needed in many locations, and that better information about multiple-cropping practices is necessary. Searle commented that an understanding of how multiple-cropping practices respond to price would be necessary to be able to attribute changes in multiple-cropping to biofuel demand. Scott and Searle agreed that we have reached broad agreement about overall LUC trends, but not about the implications of the trends, or how they may change in the future.

Dunn followed-up by asking what we can learn from analysis of recent historical data, and how we can leverage that knowledge to improve LUC modeling. Levy indicated that greater resolution of LUC patterns is necessary, and that satellite information and other remote sensing techniques could be helpful in this regard. Taheripour indicated that models are "tuned" based on current understanding of LUC, but that future modifications may be necessary as our understanding changes. Searle commented that the full impacts of commodity prices upon vegetable oils and biofuels are still uncertain.

Finally, Dunn asked whether based on retrospective analysis, we can quantitatively attribute observed LUC impacts to biofuels. Taheripour showed retrospective data illustrating increased land usage for corn and oil seed crops at the expense of pastureland, but emphasized that this does not indicate the importance of biofuels vs. other drivers in causing these changes. Scott agreed that it is not always possible to attribute specific LUC to various causes. He mentioned that other factors, such as CRP policy and broader economic drivers, may also influence LUC. Levy mentioned that because there are so many influential factors, and the impacts of biofuels upon LUC cannot be measured directly, it is necessary to utilize modeling with counterfactual scenarios. He also suggested that there are many important parameters in ILUC models that are based on expert judgment or studies that are not directly applicable, and that deriving such parameters through calibration with historical data may be helpful.

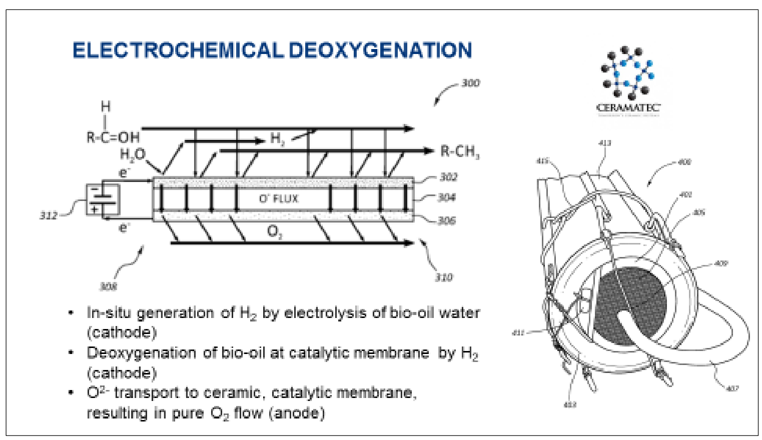
Session 2: LCA Methodology

Chairpersons: Anil Prabu (CARB) and Amit Kapur (Phillips 66)

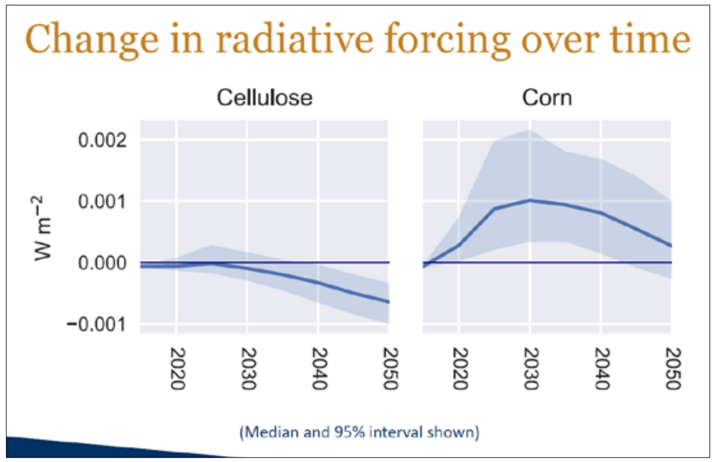
Session 2 consisted of three presentations that discussed various LCA methodological developments and related issues. Sabrina Spatari of Drexel University addressed the problem of inadequate LCA input data in the case of early-stage biofuels production technology, and showed how computational chemical modeling of target molecules could help provide some of the necessary data. Richard Plevin of U.C. Berkeley discussed use of the GCAM integrated assessment model (IAM) to conduct consequential life cycle assessment (CLCA) that examined the impacts of biofuel policies on CI and radiative forcing. Finally, Don O'Connor of (S&T)2 presented a methodological comparison of three widely used LCA models (GREET, GHGenius, and BioGrace), examining differences in their intent, structures, system boundaries, allocation methods, and data quality.

Sabrina Spatari (Drexel University) discussed some of the challenges in modeling early-stage biofuels technologies. Due to lack of relevant data regarding processing thermodynamics and cost, it is difficult to apply traditional LCA and techno-economic assessment (TEA) methodologies to evaluate early stage technologies. Spatari explained how fundamental chemical energy balance information, such as reaction enthalpies and bond dissociation energies, could be used to develop the thermodynamic data required to conduct chemical process modeling needed to perform LCA evaluations.

As an example of this approach, Spatari considered the upgrading of pyrolysis oil through a process called electrochemical deoxygenation (EDOx). As shown in the figure, this process generates hydrogen in-situ, via electrolysis of water that is contained within the pyrolysis oil. The produced hydrogen then serves to deoxygenate pyrolysis oil constituents as they pass through a membrane containing a nickel catalyst. Within this reaction environment, density functional theory (DFT), involving computational quantum mechanical modeling, can be applied to specific target molecules to investigate their reaction mechanisms and predict product outcomes. Thus, DFT can support a type of prospective LCA application, whereby simulations can be run to identify reaction conditions and chemical products having lower life-cycle energy input requirements and reduced GHG consequences.

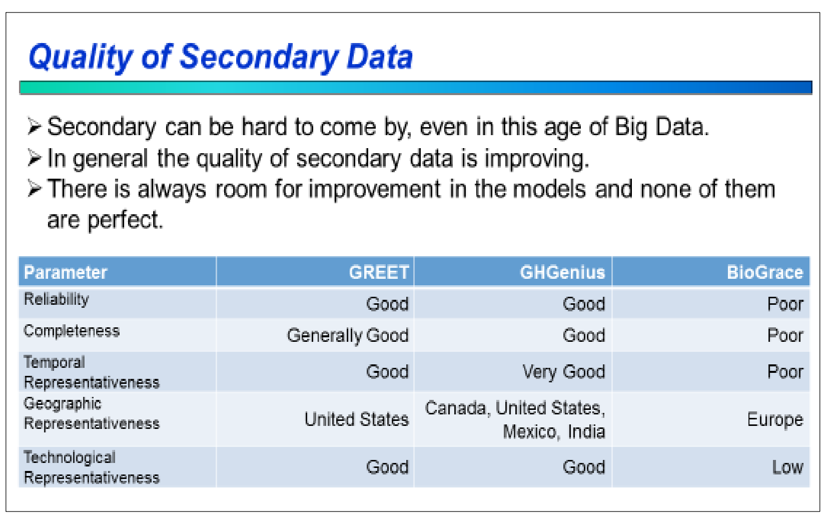


Richard Plevin (University of California, Berkeley) described a consequential life cycle assessment (CLCA) approach for biofuels using an integrated assessment model (IAM) called Global Change Assessment Model (GCAM). This approach differs from current CARB methodology, which applies an attributional life cycle assessment (ALCA) to determine the CI of the direct biofuel supply chain, then adds an ILUC CI component to estimate GHG emissions from global land use change in response to a biofuel shock. IAMs are broader in scope, in that they attempt to assess the overall effects of climate change policies on not only GHGs, but also primary energy supply, crops and forests, commodity prices, electricity production, refining, and other economic activities. Plevin mentioned several limitations of the GCAM approach, including its rather simplistic representation of biofuel technologies, lack of distinction among petroleum products, consideration of trade only for primary commodities, and others. In comparison with GTAP, which is a static general equilibrium model, GCAM is a dynamic partial equilibrium model, having 5-year time steps up to a total period of 100 years. At each step along the way, changes in model assumptions and parameters can be made.



Plevin presented an analysis of CI for corn ethanol and cellulosic ethanol that was performed using GCAM. The objective was not to determine the "best" estimate of CI, but rather to examine the sensitivity of CI to various key assumptions and model parameter inputs. About 50 parameters were perturbed to examine model sensitivity, with some of the most important ones being analytic horizon, rate of biofuel ramp-up, magnitude of CO_2 tax, energy conversion coefficients, and fraction of land that is "protected." Using a Monte Carlo simulation approach, 5000 trials were run to produce model outputs for CI, rebound effects on global fuel use, and changes in radiative forcing. As shown in the figure, the cellulosic ethanol cases produced a slight reduction in radiative forcing over the next 35 years, whereas increased radiative forcing is predicted for the corn ethanol cases. Significant rebound effects were observed to increase over time, such that the benefits of petroleum reduction may not be as large as expected. Although not definitive, Plevin concluded that according to GCAM, corn ethanol likely exacerbates climate change, while cellulosic ethanol likely mitigates it. Plevin also highlighted that the CI estimates are sensitive to a large number of assumptions and subjective choices (e.g., analytic horizon).

Don O'Connor [(S&T)^2] presented a methodological comparison of three models being used to estimate CI of biofuels: GREET, GHGenius, and BioGrace. These models have numerous differences with respect to model intent, model structure, system boundaries, allocation methods, and data quality. GREET and GHGenius were developed as broad assessment tools to inform policy over a wide range of systems and applications, while BioGrace is more narrowly focused as a compliance tool for specific biofuel pathways identified in the EU's Renewable Energy Directive (RED). Consistent with their original modeling intents, GREET



Parameter	GREET	GHGenius	BioGrace
Reliability	Good	Good	Poor
Completeness	Generally Good	Good	Poor
Temporal Representativeness	Good	Very Good	Poor
Geographic Representativeness	United States	Canada, United States, Mexico, India	Europe
Technological Representativeness	Good	Good	Low

and GHGenius include tools to assess uncertainties in the analyses, whereas BioGrace does not. There are several differences in system boundaries among the three models, with BioGrace being the most limited, consistent with its narrow focus on compliance of specified pathways. Co-product allocation is an important area of difference, with BioGrace utilizing only energy-based allocation, whereas GREET and GHGenius also include allocation based on mass and product displacement. This allocation difference drives the lower CI for ethanol and higher CI for biodiesel in BioGrace as compared to the other models.

O'Connor also discussed other changes in LCA emphasis when the models are used for policy assessment vs. compliance assessment. For compliance, such as under the California LCFS regulations, processing data measured from specific process units being considered are entered into the model. In these cases, secondary data, not related to the process units, become the focus of uncertainty and variability. These secondary data include direct energy use for feedstock production, fertilizer manufacturing, N_2O emissions, and emissions from land use changes. It is important for the secondary data being used to be consistent and of high quality. O'Connor's overall assessment of data quality among the three models is summarized in the figure. Although development of a unified model is possible, it is unlikely to occur, due to regional political and policy differences, and limitations in the required secondary data.

Panel Discussion [Moderated by Anil Prabu, (CARB)]

Prabu began the discussion by asking the panelists to identify gaps in LCA methodology that can help reduce the uncertainties associated with CI of biofuels. Spatari replied that lack of fundamental thermodynamic data limits application of the density functional theory (DFT) approach towards determining CI, but that this can be improved through use of high performance computing. O'Connor commented that confusion seems to exist between model uncertainty and variability. He mentioned that it is important for LCA developers and users to clearly distinguish between these two.

The panelists were also asked to compare ALCA to CLCA for use in a regulatory framework. Plevin responded that because the two approaches generally give quite different results, it makes no sense to use them interchangeably. ALCA doesn't seem appropriate for assessing policy implications. CLCA is better suited to assess "changes at the margin," which is what's relevant when considering policy impacts. O'Connor added that both ALCA and CLCA have utility, but the two approaches should not be combined within a single application (which is currently done in California's LCFS methodology).

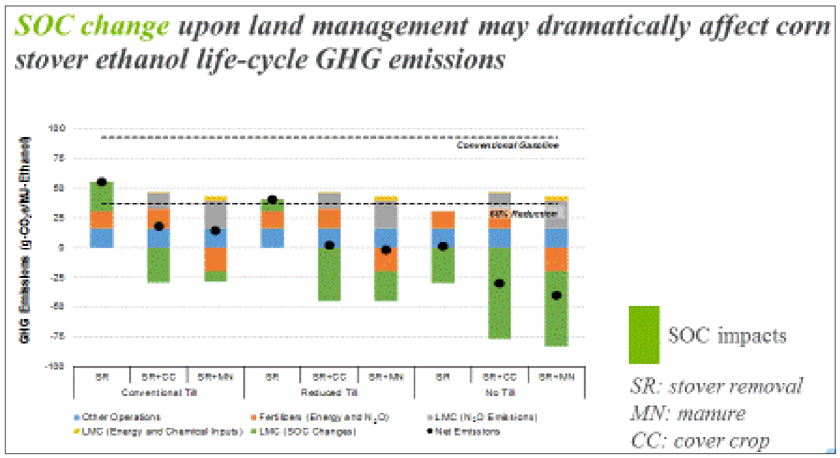
Session 3: Soil Organic Carbon

Chairpersons: Jeremy Martin (Union of Concerned Scientists) and Michael Wang (Argonne National Lab)

Session 3 consisted of four presentations that addressed the evolving understanding of soil organic carbon (SOC) and how this influences biofuel CI assessments. Zhangcai Qin of ANL discussed use of the GREET model along with the Carbon Calculator for Land Use change for Biofuels (CCLUB) model to estimate changes in SOC resulting from land transformations. Doug Karlen of USDA-ARS summarized a recent technical workshop focused on the use of crop residues for biofuels, and the associated impacts on SOC. David Clay of South Dakota State University discussed trends in SOC levels in the U.S. Midwest, and how they are influenced by land management changes. Finally, John Fields of Colorado State University explained the overall modeling approach used to estimate SOC and GHG fluxes from U.S. croplands on an annual basis.

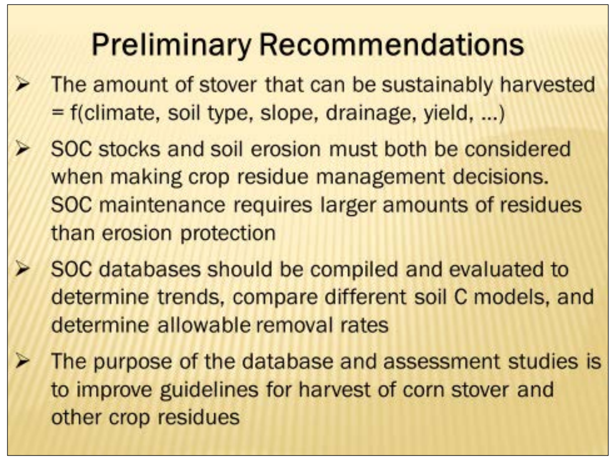
Zhangcai Qin (Argonne National Laboratory) discussed use of the GREET model to investigate how changes in SOC resulting from LUC and land management change (LMC) affect the estimated CI values of biofuels. This is done using a module in GREET called CCLUB. CCLUB utilizes information about land conversion area and type provided by Purdue's GTAP model, along with SOC information from Colorado State University's CENTURY model (and other information sources) to estimate changes in SOC resulting from specific U.S. biofuel scenarios. Currently, nine biofuel cases are considered, including biodiesel from soybean oil and ethanol from corn, corn stover, miscanthus, and switchgrass. Modeling was done to examine the spatial variation of SOC effects from cropland-pasture transition to crops and from forest transition to crops. Transitioning from cropland-pasture to corn had very little effect on SOC throughout most corn-growing regions, whereas transitioning to miscanthus generally increased SOC. In contrast, transitioning from forests to corn decreased SOC substantially in many regions, while the SOC reductions were much smaller (or even increased) if forests were transitioned to miscanthus.

Qin also presented modeling results from corn cropping scenarios in which the effects of LMC upon SOC and resulting GHG emissions were investigated. Specific LMC cases included 30% corn stover removal, application of manure, use of cover crops, and reduced tillage practices. As indicated in the figure, stover removal with conventional tillage reduces SOC levels, thus increasing lifecycle GHG emissions for stover-based ethanol scenarios. However, with reduced tillage, the SOC impacts on GHG emissions are reduced, and even become positive under no-till conditions. The use of manure and cover crops also have beneficial effects on SOC, such that the net GHG emissions under certain stover ethanol scenarios become negative, meaning that these scenarios provide overall carbon sinks. However, Qin pointed out that because these simulations of SOC change have many limitations, the results are still quite uncertain.



Doug Karlen (USDA-ARS) summarized a recent workshop entitled "Crop Residues for Advanced Biofuels: Exploring Soil Carbon Effects," that was organized by three professional societies: American Society of Agronomy (ASA), Crop Science Society of America (CSSA), and Soil Science Society of America (SSSA). This workshop was stimulated by questions regarding the appropriateness of incentives under California's LCFS program to produce cellulosic ethanol from corn stover. In particular, is it wise to promote removal of crop residues from fields when it is known that these residues provide important benefits such as reducing erosion, maintaining desirable SOC control, and improving overall soil health? The workshop was organized to address these questions and determine whether a science-based consensus could be developed regarding sustainability of crop residue harvest and SOC stocks.

The workshop consisted of six sessions, each of which focused on a specific theme: (1) soil carbon status and trends in the U.S. corn belt region, (2) modeling SOC changes, (3) measurement and verification of stover harvest/removal rates for regulatory and GHG accounting purposes, (4) geospatial variation and measurement changes in SOC and erosion risk at the field and landscape scale, (5) LCA for determining CI from crop residues, and (6) LCA of biofuels – integrating current science into policy. The complex nature of these topics was evident by some of the key issues that were identified. For example, the benefits (and dis-benefits) of residue removal are highly site specific. In most situations, retention of more residue is required to maintain adequate SOC levels than to protect against erosion. However, the rates and chemical/physical processes for conversion of crop residues to SOC are complex and influenced by many factors. As shown in the figure, four consensus recommendations were developed during the workshop. Some of the next steps include presentation of the workshop discussions and outcomes at annual meetings of the three organizing societies (ASA, CSSA, and SSSA) and preparation of a special issue of the *Agronomy Journal* devoted to these issues.

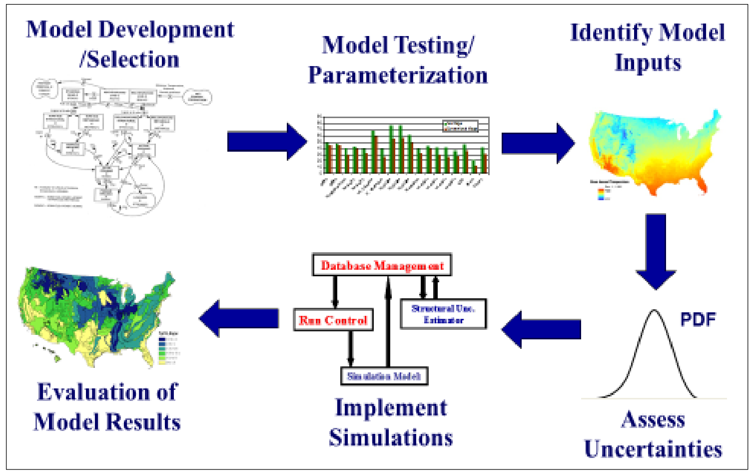


David Clay (South Dakota State Univ.) discussed the importance of soil management practices in achieving and maintaining optimum SOC levels. Soil organic matter (SOM) is essential in holding soil together, preventing erosion and increasing water-holding capacity. Due to extensive tillage operations during the late 19th and early 20th centuries, SOM in U.S. Midwest soils decreased substantially. However, with the advent of reduced tillage practices and other land management improvements, SOM has increased over the past few decades in most (but not all) locations. Knowledge about these increasing SOM levels is considered quite certain, as it is derived from many thousands of field samples taken by operators who use this information to optimize crop yields and minimize fertilizer costs. In contrast, use of the Environmental Policy Integrated Climate (EPIC) cropping system model to estimate changes in SOM over this same time period predicts much smaller increases than the measured levels. Additional work is required to investigate and understand these discrepancies.

Clay also discussed the effects of crop yield and crop residue removal on SOC levels. While SOC improvements are generally associated with higher crop yields and higher residue retention, results can be quite variable. Using the State of South Dakota as an example, the economic benefits of increasing SOC were estimated, by comparing the impacts of severe drought in 1974 (low SOC) and 2012 (high SOC). Due to the numerous land management and crop genetic improvements that occurred over this time and contributed to increased SOC levels, the overall benefits of the more resilient cropping system during 2012 were estimated to exceed 1 billion dollars.

John Field (Colorado State Univ.) described work of the Colorado State University National Resource Ecology Laboratory (CSU-NREL) in estimating soil carbon and GHG fluxes throughout the U.S. on an annual basis. This national assessment serves several purposes, including (1) provide annual reporting of GHG emissions to the U.N. Framework Convention on Climate Change (UNFCCC), (2) comply with guidelines from the Intergovernmental Panel on Climate Change (IPCC), and (3) support analyses of GHG mitigation protocols for development of domestic policy.

The overall process used by CSU-NREL consists of the six areas depicted in the figure. The fundamental underlying model, called DayCent, is used to represent GHG fluxes associated with agroecosystem biogeochemistry. DayCent utilizes daily inputs of temperature and precipitation, along with information about soil type (sand, silt, and clay) and fertilizer applications, to calculate these fluxes on a daily time step. Testing and improvement of the DayCent Model is continuously being done, utilizing data obtained from numerous experimental sites throughout the U.S. Applying DayCent on a national basis requires incorporation of several geospatial data sets, such as the USDA National Resources Inventory (NRI) of land use, PRISM weather data, and USDA crop data layer (CDL), as well as information about land management practices (tillage practices, fertilizer management, manure application, use of cover crops, and crop residue management). The uncertainties of model-predicted GHG fluxes and soil carbon stocks are estimated using probability density functions (PDF) of each model input. The final calculated results from this extensive modeling process indicates that total U.S. cropland constitutes a modest CO_2 sink, with an annual flux of approximately 27 Tg CO_2eq.



Field also presented an example of how similar modeling approaches could be applied to specific bioenergy landscape design cases to maximize cost-effectiveness of GHG mitigation. The case described involved the Abengoa cellulosic ethanol plant located in southwest Kansas. By considering tradeoffs among landscape type, management practices, and social costs, it is possible to define scenarios that optimize both ethanol production costs and GHG footprints.

<u>Session 4: Alternative Carbon Modeling Methods</u>

Chairpersons: Jeff Farenback-Brateman (ExxonMobil), Robb De Kleine (Ford), and David Lax (API)

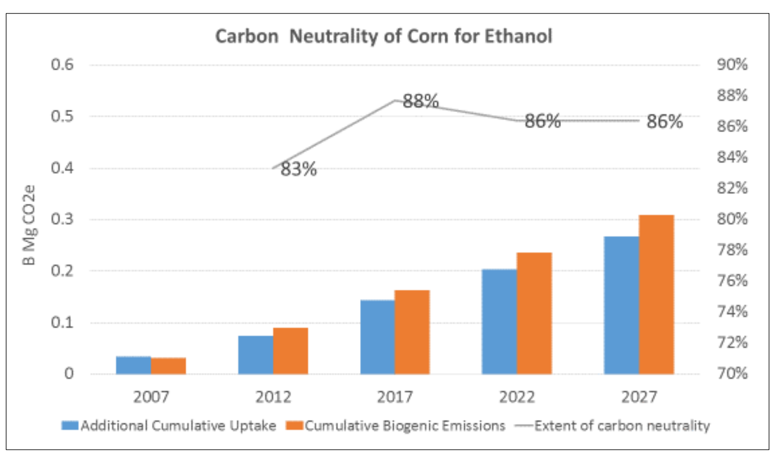
Session 4 consisted of three presentations that addressed alternative methods for modeling carbon cycles and their relevance to biofuels. Steve Peterson of Dartmouth University and Lexidyne LLC discussed system dynamics (SD) modeling approaches, and how they could be applied to evaluate various biofuel scenarios. Madhu Khanna of the University of Illinois presented work utilizing an Anticipated Baseline Approach (ABA) to estimate the extent of carbon neutrality of corn-derived ethanol, as opposed to the assumption of complete neutrality that is used in traditional LCA. John DeCicco of the University of Michigan discussed a dynamic stock and flow modeling approach that utilized an Annual Basis Carbon (ABC) accounting method to estimate the degree to which crop growth offsets biogenic emissions associated with corn ethanol.

Steve Peterson (Dartmouth University and Lexidyne LLC) described the use of a system dynamics (SD) approach to complement LCA studies with two NREL models: (1) BioLUC and (2) Biomass Scenario Model (BSM). An SD approach is useful in modeling dynamic systems by using stock and flow concepts for mass balance and including feedback loops to capture rebound effects and other indirect effects. The BioLUC model is designed to explore the effects of biofuel expansion, population trends, dietary trends, GDP growth, and other factors on LUC. In the work described here, BioLUC was used to explore four global scenarios: (1) baseline projected to 2050, (2) high biofuels case (displace 25% of petroleum), (3) high food case (double global per-capita food demand), and (4) high biofuels + high food. Results showed that in the U.S., cropland increased and available land decreased from 1990 to 2050 for all four scenarios, with the largest changes occurring in the high biofuels + high food scenario. Globally, both cropland and pastureland increased, while available land decreased over this time period.

The BSM is used by NREL to analyze how biofuels policies impact the evolution of U.S. biofuels supply chains. This model includes a representation of the U.S. agriculture system, as well as several conversion options for producing 1st and 2nd generation biofuels. Based on supply-demand relationships, BSM includes feedbacks for prices and land allocation. The model also includes a learning capability, to improve its representation of systems as additional experimental/commercial information is gained. An example was presented in which BSM was used to compare changes in the U.S. starch and cellulosic ethanol industries from 2015 to 2050. Five different scenarios were examined, in which plant techno-economics, industry maturity level, time of transition from E10 to E15, and other factors were varied. Results showed that with the most advanced scenario, the production volume of cellulosic ethanol could exceed that of starch ethanol by the year 2042.

Madhu Khanna (University of Illinois) described an alternative to the conventional LCA approach of assessing GHG savings associated with corn ethanol fuels. Typically, LCA determinations of CI for fuel pathways assume that the corn feedstock is 100% carbon neutral, thus the biogenic CO_2 emissions from the fermentation process and the vehicle tailpipe are ignored. These are very large emission sources (33 and 74 g $CO_{2\text{-eq}}$/MJ for fermentation and tailpipe emissions, respectively); thus, if the carbon neutrality is slightly less than 100%, this would have a significant effect on the overall CI values.

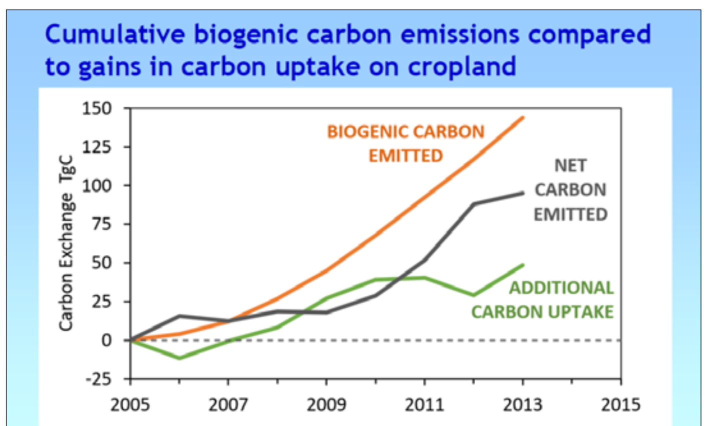
In this work, Khanna investigated the extent of carbon neutrality in corn ethanol scenarios using an Anticipated Baseline Approach (ABA), which utilized an integrated, global dynamic economic model of the agriculture, livestock, forestry, and transportation sectors. This Biofuel and Environmental Policy Analysis Model (BEPAM) was used to define a baseline scenario in which U.S. corn ethanol remained at 6.5 Bg/y from 2007 to 2017, and an RFS scenario in which the ethanol volume increased to 15 Bg/y over this period. The differences in carbon uptake between the modeled baseline and RFS scenarios is called the cumulative additional uptake. Khanna showed how the amount of cumulative additional carbon uptake increased consistently over time, as opposed to the year-by-year carbon changes in crop uptake and biogenic emissions calculated by the Annual Basis Carbon (ABC) accounting methodology published by DeCicco. One concern with ABC accounting is the strong dependence of the overall multi-year carbon uptake values on the time period selected for investigation.



Through use of this integrated modeling approach, it was shown that due to the influence of other economic factors, the amount of additional corn grown in the RFS scenario is less than would be needed to provide the required additional ethanol. For example, some corn starch is diverted from present uses (such as livestock feed) to help satisfy the increased ethanol demand. Consequently, the additional biogenic carbon uptake in the RFS scenario is less than the biogenic emissions resulting from production and use of the total corn ethanol fuel. As shown in the figure, the carbon neutrality calculated by this method varied slightly with each 5-year time-step, but was generally around 85%. Khanna also used these results to compare the direct CI values of corn ethanol determined by this ABA approach (74.1 g $CO_{2\text{-eq}}$/MJ) with that of conventional gasoline (94 g $CO_{2\text{-eq}}$/MJ). This 21% CI reduction for corn ethanol is considerably smaller than the 45% reduction determined when using a traditional LCA approach that ignores ILUC. These results differ substantially from published results using the ABC accounting methodology, where the carbon neutrality of corn cropping over an 8-year period was calculated to be only 37%, and total LCA emissions were 119 g $CO_{2\text{-eq}}$/MJ, which exceeds the value for conventional gasoline.

John DeCicco (University of Michigan) described a stock-and-flow assessment model as applied to GHG impacts of transportation fuels. He emphasized that such a dynamic method is necessary to properly characterize the actual dynamic situation, in which the biosphere is not in a steady flow equilibrium with the atmosphere. To mitigate the currently increasing amount of carbon in the atmosphere, the atmospheric uptake must be reduced (through lower emissions) or the biospheric uptake must be increased [through higher net ecological production (NEP)]. Merely replacing fossil carbon with biogenic carbon in fuels is not sufficient for reducing atmospheric uptake or increasing NEP. Thus, biofuels are not inherently carbon neutral, as is currently assumed by most LCA studies. If a biofuel is to be effective in mitigating GHGs, the benefits must be attributed to changes in NEP at locations where the biofuel feedstocks are grown.

DeCicco provided two analyses of corn ethanol cases to illustrate the stock-and-flow method of accounting for changes in net GHG emissions. The first assessment involved a single corn ethanol production plant in Illinois, and the feedstocks used to supply this plant. By comparing the carbon uptake on the cropland with the carbon flows associated with production and use of the fuels, it was concluded that net GHG emissions increased during the first year of this plant's operation. The second analysis was a broader retrospective assessment involving all major U.S. crops throughout the period of 2005-2013. The Annual Basis Carbon (ABC) accounting method was used to compare (on a year-by-year basis) carbon emissions with biogenic carbon uptake. The overall results, illustrated in the figure, indicate that only 37% of the biogenic carbon emissions associated with the production and use of biofuels over this 8-year period were "neutralized" by uptake on the cropland.



Additional carbon uptake covered only 37% of biogenic emissions over the period, and so most of the biofuel carbon was not "neutralized."

Considering that such a shortfall from full carbon neutrality may exist, DeCicco argued that with their additional process emissions and potential displacement effects, biofuels could have greater net GHG impacts compared to petroleum fuels. For example, he stated that using a 37% offset rather than a 100% offset would change a typical ALCA result of corn ethanol having a CI of 44% less than gasoline to being 27% higher than gasoline. The most significant of these displacement effects come from agricultural expansion through land conversion. DeCicco concluded that traditional LCA is not able to meet the technical needs arising from policy actions, and that use of LCA has misled policymakers. He called for new research and re-analysis, including retrospective evaluations, counterfactual analyses, and development of program-scale carbon stock-and-trade models.

Panel Discussion [Moderated by Robb DeKleine (Ford Motor Company)]

DeKleine began the discussion by asking the panelists how their alternative carbon modeling methods can be used to address policy issues. Khanna replied that her work is relevant to both research and policy questions regarding the benefits of biofuels. Her approach enables distinctions to be made among different biofuel pathways, although more work is needed to improve quantitative assessments. Peterson mentioned that system dynamics (SD) approaches are useful in exploring issues at the interface between research and policy. For example, SD can provide insights into the relationships between policy options and economic market developments. DeCicco responded that the SD approach he uses with ABC accounting is unable to provide a specific CI number for biofuels – which is what the regulatory needs demand. However, traditional LCA approaches are also unable to satisfy this demand, since it is not possible to reduce a dynamic system to a single number.

Another question asked whether dynamic effects are adequately captured in CLCA applications. DeCicco replied that CLCA doesn't require carbon mass accounting, and does not treat carbon flows in a mathematically rigorous manner. Peterson added that care must be taken to ensure that whatever modeling approach is used be as physically accurate as possible. Khanna commented that it's not just a matter of ALCA vs. CLCA, but that an appropriate carbon accounting framework must be defined in each case. Using a counterfactual modeling approach is preferred because this enables assessment of differences between a base case and a biofuel case when both are changing with time.

Session 5: LCA of Emerging Technologies

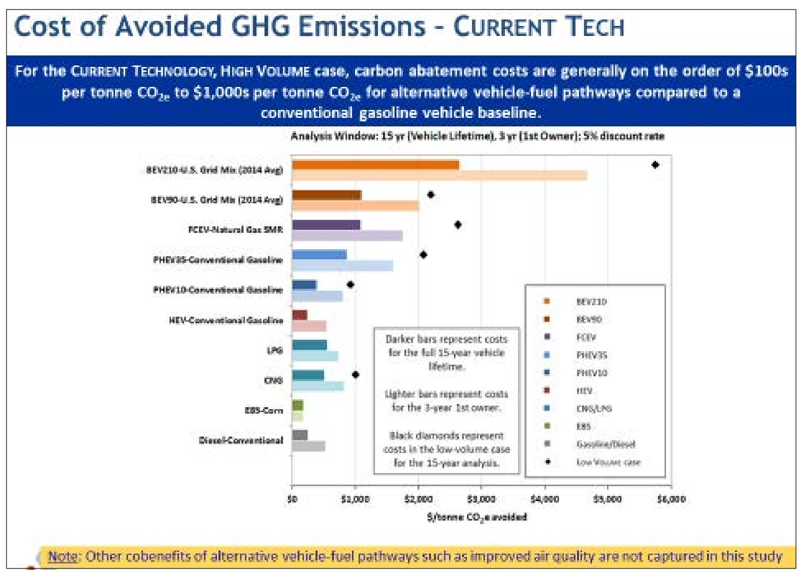
Chairpersons: Laura Verduzco (Chevron) and Devin O'Grady (Natural Resources Canada)

Session 5 consisted of four presentations focused on application of LCA to emerging technologies. Amgad Elgowainy of Argonne National Laboratory described a cradle-to-grave (C2G) analysis of current and future light-duty vehicle/fuel options with respect to GHG emissions, levelized cost of driving (LCD), and cost effectiveness of avoided GHG emissions. James Littlefield of the National Energy Technology Laboratory (NETL) discussed efforts to quantify GHG emissions associated with different stages of natural gas production, transmission, and distribution. Adrian O'Connell of the EC Joint Research Centre (JRC) discussed LCA approaches being taken by the EC to determine GHG of novel fuels produced from non-biological and/or waste feedstocks. Finally, Anil Prabu of CARB discussed approaches being considered to determine CI values for fuels that include blendstocks produced from refinery process units that co-feed petroleum and biogenic feedstocks.

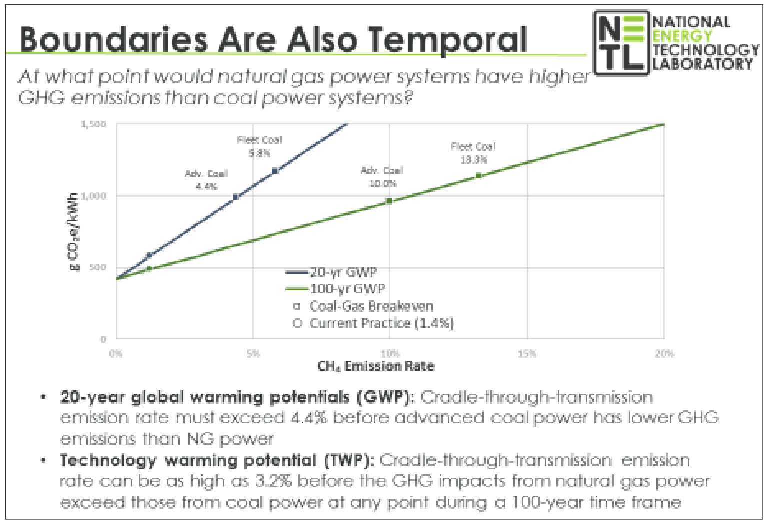
Amgad Elgowainy (Argonne National Laboratory) described a recent cradle-to-grave (C2G) analysis of light-duty vehicle (LDV) and fuel options conducted by ANL researchers and collaborators. In both the fuel cycle and the vehicle cycle GHG emissions were estimated, levelized cost of driving (LCD) was determined, and the costs of avoided GHG emissions relative to a conventional gasoline vehicle were calculated. Two time periods were considered: current (2015) and future (2030). A matrix of vehicle-fuel pathways was investigated, with vehicles including conventional internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEVs), H_2 fuel cell electric vehicles (FCEVs), battery electric vehicles (BEVs), and plug-in hybrid electric vehicles (PHEVs). Fuels included gasoline, diesel, CNG. LPG, E85, H_2, and electricity – with some of these fuels being produced through a variety of different pathways in the future scenarios. GREET was used as the modeling framework for estimating life-cycle GHG emissions resulting from both vehicle manufacturing and fuel production and use. Cost analysis was performed using DOE's Autonomie Model for the vehicle component and EIA's Annual Energy Outlook (AEO) projections for the fuel cycles. Fuel economy values (for both current and future technologies) were derived from various literature sources and were normalized to current gasoline ICE vehicles in terms of miles per gasoline gallon equivalent (MPGGE).

Total GHG emissions from each vehicle-fuel pathway were calculated as the sum of contributions from vehicle manufacturing, fuel production, and vehicle operation. In all cases, significant GHG reductions were predicted for future scenarios compared to current scenarios, due to improvements in vehicle efficiency. For example, the C2G GHG emissions from gasoline ICE vehicles were predicted to decline from about 450 g $CO_{2\text{-eq}}$/mi in 2015 to 350 g $CO_{2\text{-eq}}$/mi in 2030. Even larger reductions were predicted due to efficiency gains in other vehicle technology types. The LCD for each vehicle-fuel pathway was calculated by summing the LCD of the vehicle component and the fuel component. In all cases, total LCD was dominated by the vehicle component, which comprised 60-90% of total LCD. In the current cases, the lowest LCD value of $0.24/mile was calculated for conventional gasoline vehicles, while values for some BEV cases were over twice as large. The calculated range of LCD values in the future cases was much narrower, with most vehicle-fuel pathways falling between $0.25 and $0.40/mile.

Finally, the costs of avoided GHGs from several vehicle-fuel pathways were calculated, as compared to a conventional ICE vehicle case. As shown in the figure, the cost effectiveness of GHG reduction is much better when assessed on a 15-year vehicle lifetime (dark-colored bars) as compared to a 3-year lifetime (light-colored bars). With current technologies, the overall costs of avoided GHG emissions ranged from $200-300/tonne $CO_{2\text{-eq}}$ for conventional diesel and E85 vehicles to over $1000/tonne $CO_{2\text{-eq}}$ for fuel cell and BEV pathways. In future technology cases, the range of cost effectiveness values is expected to narrow to about $100-500/tonne $CO_{2\text{-eq}}$ for most pathways. However, it was also pointed out that significant technology and market barriers remain for some of the vehicle-fuel pathways being considered.



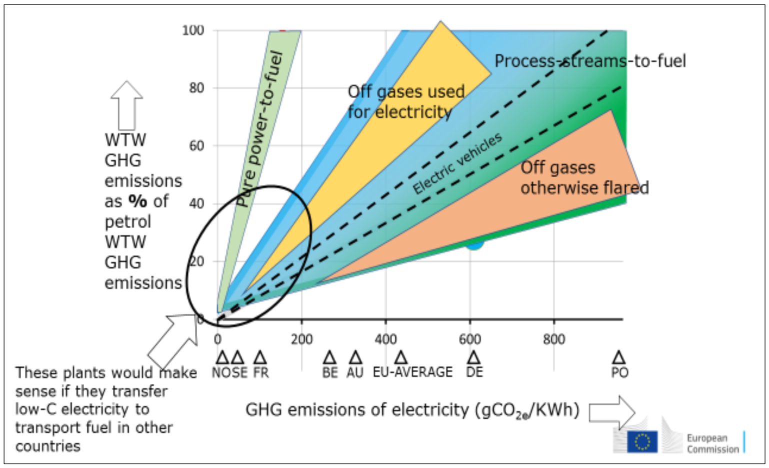
James Littlefield [National Energy Technology Laboratory (NETL)] described work being done by the LCA Program within DOE-NETL to improve understanding of GHG emissions associated with production, handling, and use of natural gas (NG) – particularly emissions of methane. In these assessments, it is important to define clearly the system boundaries being considered, as methane emission rates change substantially depending upon boundaries. For example, different emissions are associated with the four upstream stages of NG extraction, processing, transmission, and distribution. Thus, an average methane emission rate of 0.43% is determined based on NG production only, but this rate increases to 1.7% when the boundaries include production through distribution. Besides these physical/geographic boundaries, temporal boundaries are important, as the Global Warming Potential (GWP) of methane varies depending upon the time period being considered. As shown in the figure, the emissions rate “breakeven point” where NG power systems would have the same GWP as coal power systems is very different when using a 20-year GWP time frame compared to a 100-year time frame. Note that methane emissions would need to be considerably higher than present levels for NG systems to have higher GWP than coal systems under either time frame.



Littlefield also discussed development of a bottom-up methane emissions inventory of the NG life-cycle that was conducted in partnership with the Environmental Defense Fund (EDF). This study determined that pneumatic devices used in NG production and gathering activities were major sources of methane emissions, and hence present significant opportunities for emission reductions. When summing methane emissions from all known devices and sources, the total calculated bottom-up emission rate is 1.7% across the U.S. NG life-cycle. However, top-down, basin-level methane measurements generally imply higher emission rates. The differences between top-down and bottom-up results are attributed to unassigned emissions, which are not well understood and have high uncertainty.

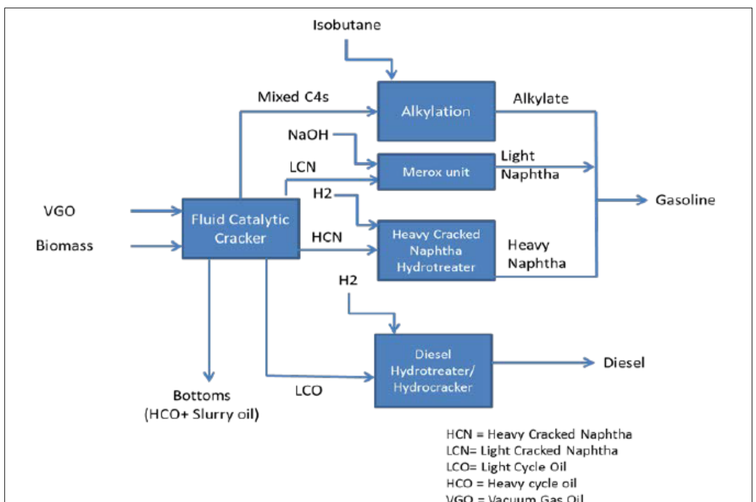
Adrian O’Connell [Joint Research Centre (JRC)] described the approach being taken by JRC, in consultation with industry groups, to develop default values for GHG savings arising from novel transport fuels. According to EC’s Fuel Quality Directive (FQD), these default values are required for fuels of two types: (1) renewable liquid and gaseous fuels of non-biological origin and (2) fuels arising from carbon capture and utilization. Limitations of using traditional attributional LCA approaches for assessing these fuels were pointed out, including inappropriate semantics and feedstock classifications. An important distinction between feedstocks is whether they are elastic (increasing with demand, such as petroleum and agricultural crops) or non-elastic (not increasing with demand, such as municipal wastes or intermediate products from existing processes). When using rigid feedstocks, the GHG savings attributable to the fuels are calculated from the emissions that would otherwise have occurred – such as from burning municipal waste or venting process gases.

Thus far, JRC has develolped four novel fuel pathways: (1) methanol synthesis from coke oven gases, (2) ethanol synthesis from industrial off-gases, (3) Fischer-Tropsch (F-T) synthetic fuels using H_2 produced from solid-oxide electrolysis cells (SOEC), and (4) ethanol produced from sewage gases utilizing a plasma reactor. O’Connell explained in detail the calculation process used to quantify the GHG savings from above pathway No.2. Formulas for determining feedstock emissions, processing emissions, and transport/ distribution emissions were defined, with input values available in lookup tables. A very important factor driving the final calculated GHG savings values is the GHG intensity of electricity production, which varies substantially among the EU member states. Consequently, a specific novel fuel pathway may be very attractive in Norway (which has a low carbon intensity electrical grid), but not in Poland (which has a high carbon intensity grid). This concept is illustrated in the figure, which shows expected ranges of GHG savings for various novel fuels as a function of electrical grid carbon intensity.



Anil Prabu (CARB) discussed issues associated with determining the yields and CI values of fuels produced in conventional refineries that employ co-processing of petroleum and biogenic feedstocks. Under California's LCFS regulations, the overall CI of transportation fuels (gasoline, diesel, and jet) must be reduced 10% from a 2010 baseline by the year 2020, with a further reduction to 18% by 2030 being contemplated. To help achieve these CI reductions, co-processing is increasingly attractive. The biogenic feedstocks being considered include pyrolysis oils, vegetable oils, tallow, and used cooking oil. Existing refinery units being considered for co-processing applications include fluidized catalytic cracking (FCC) units and hydroprocessing units. With mixed fossil and biogenic feedstocks, these process unit product streams (that are eventually blended into finished fuels) are expected to lower the CI value of the fuels. However, allocating the biogenic feedstock over the range of product streams and finished fuels is not straightforward. Furthermore, additional energy and chemical inputs to the process units (especially H_2 used in hydroprocessing units) may be necessary when operating in a co-processing mode, thus diminishing the CI benefits.

To help resolve these issues and develop a process for quantifying the volumes and CI values of co-processed fuels, CARB established a Technical Work Group that included stakeholders and subject matter experts. In addition, this group is developing guidance regarding certification of co-processed fuels, including monitoring and verification protocols. It is likely that different CI allocation methods will be used for different refinery process units. An example shown in the figure represents co-processing of vacuum gas oil (VGO) and biogenic materials in an FCC unit. In this case, the allocation method used is based on energy contents of the feedstocks and all product streams. For co-processing in hydroprocessing units, a different allocation method is proposed, to consider the incremental change in GHG emissions between a co-processing case and a base case without co-processing.



Illustrative FCC Allocation System Boundary

APPENDIX I

Glossary of Terms Used During the Workshop

ABA	Anticipated Baseline Approach
ABC	Annual Basis Carbon
AEO	Annual Energy Outlook
AEZ-EF	Agricultural Ecological Zone – Emission Factor (model)
ALCA	Attributional Life Cycle Assessment
ANL	Argonne National Laboratory
ASA	American Society of Agronomy
BEPAM	Biofuel and Environmental Policy Analysis Model
BEV	Battery Electric Vehicle
Bg/y	Billion gallons per year
BioGrace	LCA model used in EU
BioLUC	Global LUC dynamic model
BSM	Biomass Scenario Model
C2G	Cradle-to-Grave
CARB	California Air Resources Board
CCLUB	Carbon Calculator for Land Use change for Biofuels
CDL	Cropland Data Layer
CEAP	Conservation Effects Assessment Project
CGE	Computable General-Equilibrium
CI	Carbon Intensity; also Compression Ignition
CLCA	Consequential Life Cycle Assessment
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
$CO_{2,eq}$	Mass of a specified GHG expressed as a mass of CO_2 having equivalent GWP
CoA	(USDA) Census of Agriculture
CONCAWE	CONservation of Clean Air and Water in Europe
C-P	Cropland-Pasture
CRC	Coordinating Research Council
CRP	Conservation Reserve Program
CSSA	Crop Science Society of America
CSU-NREL	Colorado State University – Natural Resource Ecology Laboratory
DayCent	Ecosystem model for soil carbon
DFT	Density Functional Theory
DOE	(US) Department of Energy
EC	European Commission
EDF	Environmental Defense Fund
EDOx	Electrochemical Deoxygenation
EF	Emission Factor
EIA	Energy Information Administration
EIO-LCA	Economic Input-Output- Life Cycle Assessment Model
EISA	(US) Energy Independence and Security Act

EPA	(US) Environmental Protection Agency
EPIC	Environmental Policy Integrated Climate model
EU	European Union
EV	Electric Vehicle
FAO	(UN) Food and Agricultural Organization
FAPRI	Food and Agricultural Policy Research Institute
FASOM	Forest and Agricultural Sector Optimization Model
FCC	Fluidized Catalytic Cracking
FQD	Fuel Quality Directive
F-T	Fischer-Tropsch
g $CO_{2,eq}$ MJ^{-1}	grams of CO_2, equivalents per MJ of fuel
GCAM	Global Change Assessment Model
GDP	Gross Domestic Product
GGE	Gasoline Gallon Equivalent
GHG	Greenhouse Gas
GHGenius	LCA model used in Canada
GHGI	Greenhouse Gas Inventory
GLOBIOM	Global Biomass Optimization Model
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GTAP	Global Trade and Analysis Project
GWI	Global Warming Intensity
GWP	Global Warming Potential
Ha	Hectare
IAM	Integrated Assessment Model
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
ILUC	Indirect (or Induced) Land Use Change
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IV	Instrumental Variable
JRC	(EC) Joint Research Centre
LCA	Life Cycle Assessment
LCD	Levelized Cost of Driving
LCFS	Low Carbon Fuel Standard (California regulation)
LDV	Light-Duty Vehicle
LEM	Life Cycle Emissions Model
LMC	Land Management Change
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LUC	Land Use Change
MMT	Million Metric Ton
MPGGE	Miles Per Gallon Gasoline Equivalent

N_2O	Nitrous Oxide
NBB	National Biodiesel Board
NEP	Net Ecological Production
NETL	(DOE) National Energy Technology Laboratory
NG	Natural Gas
NPV	Net present value
NREL	National Renewable Energy Laboratory
NRI	(USDA) National Resources Inventory
ORNL	Oak Ridge National Laboratory
PDF	Probability Density Function
PHEV	Plug-in Hybrid Electric Vehicle
RED	Renewable Energy Directive
RFS	Renewable Fuels Standard
SD	System Dynamics
SI	Spark Ignition
SOC	Soil Organic Carbon
SOEC	Solid Oxide Electrolysis Cell
SOM	Soil Organic Matter
SSSA	Soil Science Society of America
TEA	Techno-Economic Assessment
TRL	Technology Readiness Level
UIC	University of Illinois-Chicago
UNFCCC	UN Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VGO	Vacuum Gas Oil
WTW	Well-to-Wheels