Summary of

CRC Workshop on Life Cycle Analysis of Transportation Fuels

Argonne National Laboratory
October 26-28, 2015

A. Introduction

On October 26-28, 2015, 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, CONCAWE, Canadian Fuels Association, National Biodiesel Board, Renewable Fuels Association, South Coast Air Quality Management District, US Department of Agriculture, and the University of Michigan Energy Institute. This was the fourth in a series of bi-annual LCA Workshops organized by CRC. The goals for 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 126 total attendees from 10 countries, including 29 international attendees. Representatives were present from government bodies, industry, academia, and non-governmental organizations (NGOs). Twenty-four presentations were given, organized into five Technical Sessions. In addition, an Opening Session provided background information about CRC, and set the context for this Workshop by summarizing the previous three LCA Workshops. A brief summary of a Biodiesel Feedstock Workshop, held immediately prior to the LCA Workshop, was also presented. Finally, a closing panel discussion session was held, with a focus on identifying improvements that have been made in the LCA area, and high priority issues that require additional work.

This 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 Workshop Summary 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 highlights from the LCA Workshop. This list is not comprehensive, but attempts to capture the most significant take-home messages, common themes that emerged, and conclusions where there appeared to be some degree of consensus.

- Additional progress has been made during the past two years (since the previous workshop) in LCA of transportation fuels. On-going improvements in model structure and underlying databases appear to be reducing the large disparity among results that previously existed for similar fuel pathways, and have increased overall confidence in LCA results. Nevertheless, several longstanding problems – such as data quality and model uncertainty – require further attention.
- The issue of indirect land use change (ILUC) remains controversial – both in principle and in application. Recent revisions to ILUC models have reduced the estimated ILUC effect on the carbon intensity (CI) of some biofuels, but large uncertainties remain.
- Some regulatory applications of LCA have become clearer and more firmly entrenched. Over the past few years, the U.S. EPA has not significantly changed its methodologies for assessing the GHG reduction potential of biofuels, including the contribution of ILUC, but has applied these methodologies to a wider range of fuel pathways. The California Air Resources Board (CARB) has changed its LCA methodologies significantly by adopting an updated agro-economic model (GTAP-BIO) and underlying databases used to determine ILUC and its contribution to a fuel's CI value. In Europe, although ILUC GHG values have been proposed for key biofuel pathways, the application of ILUC is still not formally included in renewable fuel requirements. However, volume limits have been established for 1st generation biofuels.
- The issue of biofuel sustainability is gaining increased attention. The EU has adopted amendments to the Renewable Energy Directive (RED) that incorporate sustainability criteria for biofuels, and efforts are now underway to define a sustainability certification process.
- Several speakers addressed the global issue of a bio-based economy (BBE) and the role of biofuels within such a system. To produce sufficient food and energy for a growing global population, while reducing GHG emissions, requires large-scale agricultural modernization, use of agricultural residues for energy, and improved efficiency in use of all resources.
- The issue of co-product allocation, which was a major topic of earlier Workshops, received much less attention at this Workshop. While uncertainties remain, this issue seems to have become less controversial through increased transparency in how co-product allocation is being treated in each LCA study.
- Initial modeling investigations have shown that non-GHG climate forcers can also affect the lifecycle global warming potential (GWP) of biofuels. In particular, the short-lived climate forcers of black carbon (BC) and primary organic carbon (POC) appear to have non-negligible effects for certain biofuel pathways. Changes in surface albedo due to biofuel-induced LUC may also be important.
- On-going work is focused on understanding the sensitivities of LCA model results to changes in model inputs. This is helping to identify priority areas where further improvements in data or model structure would be most beneficial.

- The topics of model variability and uncertainty are continuing to receive attention. Formal uncertainty analysis techniques are being applied to LCA data and modeling results, leading to better understanding of uncertainty ranges. Overall uncertainty for a specific biofuel's CI value is strongly influenced by soil N_2O emission rates and LUC estimates, among other factors. While presenting uncertainty estimates as probability distributions is scientifically useful, translating this information into regulatory standards remains problematic.
- Over the past decade, significant amounts of LUC have been observed globally – both in the form of intensification and extensification. In some cases, this appears to be driven by non-biofuel factors, including population growth, availability of frontier lands, and national policies. Compared to other regions of the world, relatively little LUC (either intensification or extensification) has occurred in Europe or the U.S. over this period.
- Considerable progress has been made in defining and mapping LUC – especially in the U.S. This has been enabled by application of satellite remote sensing, aerial photography, and other information sources – and by development of analytical tools to process and interpret this information. Such work is improving our ability to determine LUC with greater spatial and temporal specificity.
- Advancements are being made in understanding and modeling of how land conversions to 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. These factors have important implications for accurate assessment of a biofuel's GHG impacts.
- Considerable efforts are being applied to determine CI values for baseline fossil fuels. Models and underlying data are being improved to better understand the range of GHG effects across different crude oil types and different refinery configurations. Largely due to greater refinery complexity and the ability to process a wider range of crudes, petroleum fuels produced in the U.S. and Europe have higher CI values than those produced elsewhere. CI values of petroleum fuels are gradually increasing, due to greater use of unconventional petroleum resources, though this increase is partially mitigated by reductions in flaring operations in oil fields.
- Several organizations are investigating high octane fuel (HOF) options, and how they could affect vehicle efficiency and overall life cycle GHG emissions. Initial findings suggest that with higher ethanol blends in the HOFs (E20-E40), increased emissions from fuel production are offset by decreased vehicle emissions (due to improved vehicle efficiency), resulting in an overall life cycle GHG benefit of such fuels.

C. Session Summaries, Information Gaps and Data Needs

Session 1: Regulatory Environment/ New Policies Driving LCA Pathways and Methodologies

Session 1 presented an overview of transportation fuel policies that are driving the development and implementation of LCA methodologies. Particular regions/jurisdictions discussed included the entire U.S., California, and the EU. In each case, the definition and application of LCA is somewhat different. The concept of indirect land use change (ILUC) and its impact on the overall carbon intensity (CI) of a fuel are included explicitly in California's Low Carbon Fuel Standard (LCFS). With adoption of recent updates to its LCA methodologies, CARB has determined lower contributions of ILUC to the CI values of biofuels than previous estimates. Under the U.S. Renewable Fuel Standard (RFS) regulations, specific volumes of fuel in each of four categories are required, with each category having a GHG reduction target. These targets are based on LCA evaluations that include ILUC estimates. In the EU, the Renewable Energy Directive (RED) defines a volume target of 10% renewable fuel by 2020, and its Fuel Quality Directive (FQD) requires a 6% reduction in life cycle GHG. Although ILUC is not explicitly considered in determining this GHG reduction, the EU has instituted a cap on the amount of 1st generation biofuels that can be used, as well as a biofuel sustainability certification process. While the legislative framework for renewable fuels and GHG reduction is well developed within the EU, Member States have some flexibility in how they implement specific actions.

Session 2a: LCA Gaps, Uncertainties, and Methodology Development: General LCA Issues

Session 2a addressed several general issues related to LCA of bioenergy and biofuels. It was pointed out that the assumption of bioenergy being carbon neutral is too simplistic. Bioenergy must be viewed within the broader context of global carbon balance, where the net GHG emissions are influenced by numerous factors. Total carbon balance is poorly understood, with large uncertainties even in relatively data-rich locations. To satisfy the increasing food and energy needs of a growing population, greater intensification of land use is necessary. This may be possible without increasing GHG emissions through modernization of agriculture, utilization of degraded lands, and more efficient use of all resources. Utilization of prime agricultural lands for growing energy crops introduces several concerns, but greater use of agricultural residues for energy production is generally desirable.

Session 2b: LCA Gaps, Uncertainties, and Methodology Development: Co-Product Methods and Feedstock-Related Issues

Session 2b addressed several specific issues related to LCA of transportation fuels. Co-product allocation is critical in determining how much GHG emissions are attributed to a specific fuel. Several different attribution methods are commonly used; there is not always agreement on which method is the most appropriate in a particular situation. Non-GHG contributions to climate forcing are beginning to receive more attention. Two short-lived climate forcers – black carbon (BC) and primary organic carbon (POC) – are important in the life cycle of biofuels, and contribute to the fuels' overall global warming potential (GWP). Land use change (LUC) induced by biofuels can also change the surface albedo of the converted land, which could result in either warming or cooling effects. Assessment of LCA uncertainty is on-going. When using the GREET model to evaluate corn ethanol pathways, parameters related to LUC and soil N_2O emissions appear to most strongly contribute to overall uncertainty of life cycle GHG emissions. Large-scale deployment of energy crops is expected to produce significantly lower yields than reported from small-scale trials. Yet, updates to ORNL's Billion Ton Study (BTS) indicated that with biomass costs of $60/ton in 2030, sufficient feedstock could be available in the U.S. to produce over 2-times the EISA requirement of 36 bg/y of renewable fuels.

Session 3: Advances in Biofuel Modeling: LUC and Advanced Biofuels

Session 3 addressed recent and on-going improvements in modeling of LUC and its impact on life cycle GHG emissions of biofuels. Numerous improvements have been incorporated into the CGE model GTAP, and a GTAP-BIO database has been developed for use in modeling biofuel applications. Use of this updated model and database in CARB's LCFS regulations has resulted in reduced ILUC contributions to the carbon intensity (CI) of most biofuels. During the past decade, considerable LUC has been observed in many countries/regions throughout the world. Extensification has been most significant in locations that have frontier land available, while intensification is more significant in areas with growing populations but limited frontier land. Besides biofuels policies, other socioeconomic factors are drivers for global LUC. Within the U.S., satellite imaging and other tools are being applied to map LUC with greater spatial and temporal resolution than before, and to distinguish between different types of crops. Advancements are being made in understanding and modeling of how land conversions affect soil organic carbon (SOC). Also, land management change (LMC) scenarios – such as removal of corn stover, application of manure, and introduction of winter cover crops – have important impacts on carbon stocks and their GHG implications. In the EU, a partial equilibrium model called GLOBIOM is being used to estimate ILUC and its GHG effects for many different biofuel scenarios. Also in the EU, "consequential thinking" is being applied to attributional LCA to develop modeling methods for evaluating GHG and other environmental impacts of bioenergy and biofuel pathways.

Session 4: Advances in LCA of Petroleum/Alternatives

Session 4 addressed LCA assessments and applications involving petroleum-derived fuels and other non-biofuel applications. The Petroleum Refinery Life Cycle Inventory Model (PRELIM) has been developed (and improved) to estimate GHG and energy impacts of producing transportation fuels in North American refineries. GHG emission vary over a wide range (20-100 kg CO_{2eq}/bbl), depending upon the quality of the crude oil and the configuration of the refinery. On a global basis, GHG emissions of producing and transporting petroleum-based fuels (well-to-pump basis) vary with crude type and the degree of refinery complexity. In general, refinery complexity is highest in North America and lowest in Africa. Several groups have begun to investigate the potential impacts that use of high octane fuels (HOFs) could have on life cycle GHG emissions. [The definition of HOF is not clear, though several speakers referred to fuels having Research Octane Numbers (RON) of around 100.] Blending high levels of ethanol into gasoline (E25-E40) is one way to achieve HOFs. GREET modeling suggests that such high ethanol fuels would provide life cycle GHG benefits compared to baseline E10 gasoline. Refinery modeling indicates that CO_2 emissions increase when refinery operations are modified to produce suitable blendstocks for oxygenate blending (BOBs). However, use of HOFs enables more efficient engine operation, which results in an overall net reduction in GHG emissions. Widespread introduction of HOFs into the marketplace raises numerous challenges. One suggested approach is to gradually change the ratio of Premium/Regular grades of gasoline from the current level of about 10/90 to a future level of 80/20.

D. Highlights and Learnings from Individual Presentations

Opening Session: Background of CRC LCA Workshops

Chairpersons: Vincent Camobreco (US EPA) and Jeff Farenback-Brateman (ExxonMobil)

Brent Bailey (CRC) provided a brief history of CRC and gave a few examples of activities since its establishment as an independent organization in 1942. The objective of CRC, as stated in its charter, is "To encourage and promote the arts and sciences by directing scientific cooperative research in developing the best possible combinations of fuels, lubricants, and the equipment in which they are used, and to afford means of cooperating with the Government on matters of national interest within the field." CRC's permanent membership includes most major automobile and petroleum companies. While research activities initially focused on optimizing fuel and lubricant usage in automotive equipment, CRC has actively promoted environmental research since the 1960's. The current interest in LCA of transportation fuels is an outgrowth of CRC's air quality research. The series of LCA Workshops organized by CRC (this being the 4ths such workshop) is an example of the organization's efforts to promote and coordinate broad participation by stakeholders from industry, government, and NGOs.

Jeff Farenback-Brateman (ExxonMobil) provided an historical perspective on the topic of LCA of transportation fuels. He noted regulatory actions by California (2007), the US EPA (2007), and the EU (2009); all of which promote renewable fuels that reduce greenhouse gas (GHG) emissions as determined on a life-cycle basis. The California Low Carbon Fuel Standard (LCFS) and the federal Renewable Fuel Standard (RFS) also require consideration of GHG impacts from indirect land use change (ILUC) associated with increased production of biofuels. To investigate implications of these LCA-based regulations, numerous scientific studies have been conducted. Several influential publications appeared in the late 2000s, which arrived at dramatically different results, particularly for ILUC impacts. The primary motivation for this series of CRC-sponsored LCA workshops was to understand the reasons for such differing results, and to prioritize future research that would reduce uncertainties. As explained by Farenback-Brateman, the goals have remained fairly constant throughout all four LCA workshops held thus far. (The four stated workshop goals are identified in the Introduction Section of this report.) He also provided brief summaries of the previous workshops, and aspirations for the current workshop:

- 2009 Workshop: "Getting our feet wet; focus on biofuels"
- 2011 Workshop: "The science is advancing, but uncertainties remain"
- 2013 Workshop: "Mind the gap"
- 2015 Workshop: "The more we know, the less we know"

Session 1: Regulatory Environment/New Policies Driving LCA Pathways and Methodologies

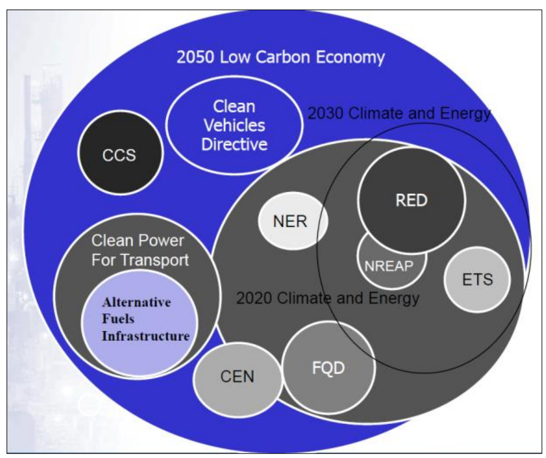
Chairpersons: Vincent Camobreco (US EPA), Jim Duffield (USDA), and Jeff Farenback-Brateman (ExxonMobil)

This session consisted of four presentations that provided an overview of national, international, and state efforts to implement and/or revise renewable fuel and other climate-related transportation fuel policies. International perspective was provided by Chris Malins of the International Council on Clean Technology (ICCT) and by Heather Hamje of Conservation of Clean Air and Water in Europe (CONCAWE). A U.S. national perspective was given by Vincent Camobreco of the U.S. EPA. Anil Prabhu of the California Air Resources Board (CARB) provided an update of that state agency's activities.

Chris Malins (ICCT) presented an overview of renewable fuel policies and activities in many locations throughout the world. In the EU, the Renewable Energy Directive (RED) and the Fuel Quality Directive (FQD) are the primary policy drivers for increased use of biofuels. The RED has a target of 10% renewable transport fuels by 2020. This Directive does not strictly account for GHG emissions arising from indirect land use change (ILUC), but does cap the amount of food-based biofuel at 7% of total transport fuels, and includes a target of 0.5% biofuels from second generation feedstocks. There are no RED targets set beyond 2020, and it is unclear what form of support for renewable fuels will exist at that time. In the U.S., the federal Renewable Fuel Standard (RFS) is the principal mechanism for dictating supplies of biofuels. However, there is lack of clarity regarding future volumes, as barriers exist to increased use of conventional biofuels, and serious challenges remain to producing cellulosic biofuels. In Brazil, sugarcane ethanol usage remains high and relatively stable at 25% of the gasoline market, and biodiesel at 7% of the diesel market. In Indonesia, a palm oil export levy has been introduced to support in-country expansion of biodiesel, which is expected to satisfy 25% of the diesel market by 2025.

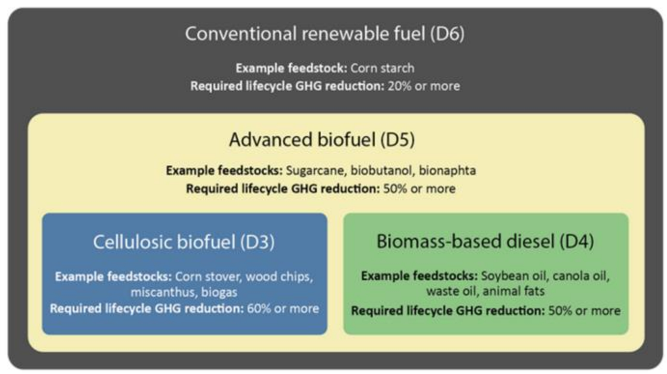
Low carbon fuel standards (LCFS) are beginning to be implemented and strengthened. This trend is led by California, where LCFS regulations have recently been re-adopted, and now contain greater financial market certainty. Adoption of similar LCFS policies is occurring in Oregon, British Columbia, and Germany – but prospects for expansion to other regions appear limited at present. The International Civil Aviation Organization (ICAO) is discussing market-based measures to ensure carbon-neutral growth beyond 2020, but the details of this are not yet defined. In closing, Malins offered three observations: (1) cellulosic fuel production incentives may be firming up, (2) adoption of biofuel policies in the developing world has slowed, and (3) new fuel technologies raise new sustainability questions.

Heather Hamje (CONCAWE) summarized the status of European transportation regulations related to renewable fuels. While CO_2 emissions from most sectors within Europe have been declining over the past 20-years, this is not true for the transport sector, which is now responsible for 20% of total EU emissions. There are challenges to reduce transportation-related GHG emissions both upstream [well-to-tank (WTT)] and downstream [tank-to-wheels (TTW)]. To address this situation, a complex EU legislative framework has developed, which is illustrated by the figure shown here. A major component of this framework, is the Renewable Energy Directive (RED; 2009/28/EC), which was implemented in 2009. Among other requirements, the RED set targets for 20% total renewable energy by 2020, as well as 20% improvement in overall energy efficiency. Also implemented in 2009 is an amendment to the Fuel Quality Directive (FQD; 2009/30/EC) that allows an increase in biodiesel content to B7 and requires an overall reduction of life cycle GHG emissions from transportation fuels of 6% by 2020. This amendment also incorporated sustainability criteria for biofuels that are used to meet the GHG reduction requirement. In April of 2015, the European Parliament adopted the RED/FQD review. This so-called "ILUC Directive" caps 1st generation biofuels at 7% of total transportation fuels and includes ILUC reporting requirements. Also, incentives were incorporated for electrification of road transport and for using biofuels derived from non-food feedstock.



Efforts are underway to define and improve biofuel sustainability certification processes that encourage meaningful reduction of life cycle GHG emissions while avoiding environmental harm. This is a complex area requiring effective chain of custody procedures, standardization of calculations, proper labeling, use of auditable methods, and other factors. In summary, Hamje emphasized that renewable fuels make an important contribution towards the EU meeting its overall renewable energy targets.

Vincent Camobreco (US EPA) gave an overview of the RFS program and presented updates of EPA's recent activities in this area. In the U.S., the RFS is the primary tool driving introduction of low carbon intensity fuels. As part of the Energy Independence and Security Act of 2007 (EISA), Congress established four nested categories of renewable fuel, each of which has a required GHG reduction threshold value (see figure). Annual volume requirements for each biofuel category were originally defined in the 2007 Energy Independence and Security Act (EISA), reaching a total of 36 billion gallons/year (bg/y) in 2022. However, EPA has the authority to review and adjust these volumetric requirements annually. By the end of November, 2015, EPA is expected to take final action on proposed volumetric requirements for the years 2014-2016. EPA has also expanded the number of renewable fuel pathways accepted under RFS, and has streamlined the process for dealing with new pathway petitions. Recently adopted pathways include compressed and liquefied natural gas (CNG and LNG) produced from biogas, and electricity (for EVs) produced from biogas. Each pathway includes three elements: feedstock, production process, and fuel.



To estimate the indirect GHG emissions associated with biofuels, EPA uses a mix of attributional and consequential life-cycle analysis (ALCA and CLCA) approaches. These methods are used to determine whether a biofuel meets the GHG reduction threshold for the appropriate renewable fuel category (see figure). However, for climate policy purposes, the transportation sector is evaluated on the basis of fuel volume usage times GHG intensity of the fuel. It was pointed out that there are several ways to estimate GHG intensity, not all of which include an LCA approach. Currently, EPA, CARB, and IPCC all use different approaches to determine GHG intensity. Camobreco indicated that by their nature, LCA-based accounting approaches are broad reaching and capture emissions impacts in different sectors, thereby helping to control for leakage and incentivizing best practices across different sectors.

Anil Prabhu (ARB) presented an update on California's LCFS program, which was originally adopted in 2009, amended in 2011, and re-adopted in 2015. LCFS requires a 10% reduction in the carbon intensity (CI) of the overall transportation fuel pool by 2020. CI is based on well-to-wheels LCA of fuels used in California. It is expressed as g CO_{2eq}/MJ, and includes GHG emissions resulting from ILUC. A compliance curve of declining CI values for the entire fuel pool is defined between 2010 and 2020. Thus far, suppliers are "over-complying," meaning that credits are being accumulated, which can be used later to offset deficits. Most credits to-date have been generated by corn ethanol, but ARB projects larger contributions in the future from other low-carbon fuels – including sugarcane ethanol, biodiesel, renewable diesel, electricity, and renewable natural gas.

In ARB's recent re-adoption process, updated analysis tools were developed and applied to determine CI values. This included use of the CA-GREET model to determine the direct CI of biofuel production and use, and the OPGEE model to determine the direct CI of petroleum production and transport. For indirect CI, this included the GTAP model to determine ILUC, and the AEZ-EF model to determine the GHG emissions associated with this LUC. Application of these updated tools has resulted in lower CI values for all the major biofuels currently used in California (corn ethanol, sugarcane ethanol, soy biodiesel, and soy renewable diesel). These reductions are largely attributed to lower ILUC estimations.

Existing fuel pathways must now be re-certified under the re-adopted LCFS process. At present, there are 363 potential pathways, with about 300 of these being classified as "Tier 1." Such pathways involve 1st generation biofuels, which can be re-certified through a relatively simple process. Tier 2 pathways, which involve more advanced biofuels, require greater efforts for re-certification. The re-adoption process also introduced a cost-containment feature, with a compliance cap of \$200/ton CO_{2eq}. It is believed that this will strengthen incentives to invest in low-CI fuels and will prevent extreme market volatility.

Session 2a: LCA Gaps, Uncertainties, and Methodology Development: General LCA Issues

Chairpersons: Jeremy Martin (Union of Concerned Scientists), Don Scott (NBB), and Michael Wang (ANL)

Session 2a dealt with general LCA issues, including biomass accounting approaches, potential GHG effects of biomass resources, and various improvements and limitations to LCA modeling approaches. The session began with Helmut Haberl of Alpen-Adria-Universitat Klagenfurt who discussed the role of biomass/bioenergy in the global carbon balance. This was followed by Andre Faaij of the University of Groningen who discussed the role of agriculture and bioenergy within a bio-based economy, and by Edward Smeets of Wageningen University who discussed options for large-scale deployment of biomass-to-energy systems. Rich Plevin of U.C. Davis had planned to speak about consequential LCA to estimate climate change mitigation benefits of fuel policies, but was unable to attend.

Helmut Haberl (Alpen-Adria-Universitat Klagenfurt) discussed the issue of carbon accounting as related to bioenergy. He pointed out that the conventional wisdom of bioenergy being carbon neutral is too simplistic, and that the net GHG emissions are influenced by many different factors. The most appropriate comparison is between the net biosphere carbon flux in the presence of bioenergy systems compared to the flux in the absence of such systems. To feed the growing global population, total agricultural output must increase 70-100% by 2050. However, humans already use 3/4 of the world's ice-free land, and much of the remaining land is infertile. Therefore, intensification of existing land is essential. This intensification can be expressed as the global human appropriation of net primary production (HANPP), which has already increased from 13% in 1910 to 25% in 2007, and is expected to further increase to 45% by 2050 to satisfy both human food and bioenergy needs.

The total stocks and flows of carbon – and hence the global carbon balance – is poorly understood. As an example, Haberl indicated that the two most widely used estimates of global carbon stocks in forests differ by an amount that is 10 times as large as current global annual fossil-related CO_2 emissions. It is even difficult to achieve an acceptable carbon balance in the rather small and well-understood region of Austria. With many variables involved, it is not clear whether bioenergy crops (switchgrass or short rotation coppicing) provide greater GHG reduction benefits compared to afforestation of the same land.

Andre P. C. Faaij (University of Groningen) explained the need to develop a global bio-based economy (BBE) – including bio-carbon capture and sequestration (bio-CCS), which has negative carbon emissions – if we are to feed the global population while remaining within the 2°C temperature rise target. He suggested that sustainable biomass resources in the future could be sufficient to supply 300

EG/year of energy, as compared to current global energy use of 550 EJ. However, to achieve this would require modernization of agriculture; utilization of degraded lands; and improved efficiency of use for all land, water, and nutrients.

Faaij suggested that the ILUC risks associated with biofuel expansion could be mitigated (or eliminated) by measures that improve productivity of agriculture and livestock. He urged comparison of bottom-up and top-down ILUC modeling, believing that this could reveal insights that reduce the risk of ILUC emissions. With application of effective, regionally-specific mitigation measures, ILUC emissions could become negative. However, biofuels and ILUC are just part of the picture – an effective BBE requires consideration of biofuels within the broader context of bioenergy, modernization of agriculture, and more efficient use of natural resources.

Edward Smeets (Wageningen University) described a modeling study to investigate the land use change (LUC) and food security effects of large-scale use of bioenergy from forest/agricultural residues and from biomass plantations (meaning switchgrass or short-rotation woody crops). Based on work by Daioglou et al. (2015) using the Integrated Model to Assess the Global Environment (IMAGE), the global sustainable potential of forest and agricultural residues is estimated to be 33 EJ/year (in 2011). This amount is similar to expected biomass demand in 2030 (35 EJ/year) to produce bioelectricity and 2nd generation biofuels. A computable general equilibrium (CGE) model called Modular Applied GeNeral Equilibrium Tool (MAGNET) was used to examine two options with respect to location of the plantations: (1) land that competes with agricultural land and (2) land that is not suitable for conventional agriculture.

Model results indicated that placement of plantations on agricultural land is not attractive, due to much higher prices of this agricultural land. On the other hand, increased use of agricultural residues increases the profitability of crop production. This causes greater food production and lower prices for agricultural commodities, which improves food security in some areas. The impacts of greater agricultural residue usage upon global LUC appears to be quite small, and involves conversion of pastures to cropland. A LUC range of 0.4 – 1.3 Mha/EJ was estimated for agricultural residues, as compared to 27-28 Mha/EJ for 1st generation biofuels. The GHG impacts of this LUC have yet to be calculated.

Session 2b: LCA Gaps, Uncertainties, and Methodology Development: Co-Product Methods and Feedstock-Related Issues

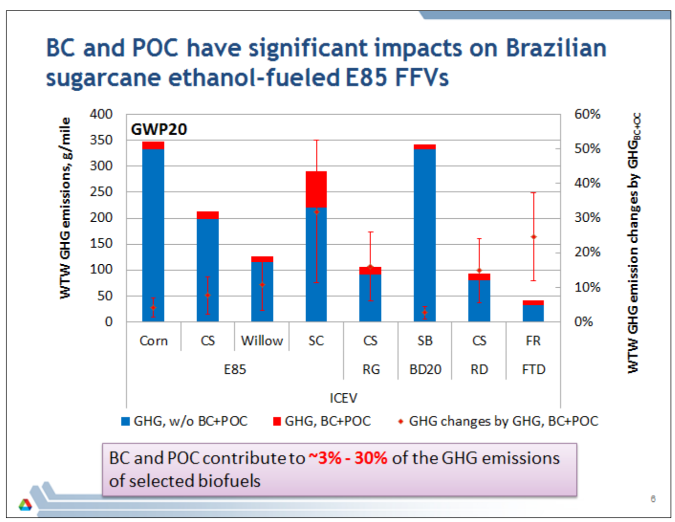
Chairpersons: Jeremy Martin (Union of Concerned Scientists), Don Scott (NBB), and Michael Wang (ANL)

Session 2b consisted of five presentations that addressed specific LCA issues such as co-product methods and effects, incorporation of non-GHG climate change factors, and biomass yield limitations. Mark Staples of MIT began with a discussion of co-product allocation methods in LCA of alternative jet fuels, followed by Hao Cai of Argonne National Laboratory (ANL) who discussed climate effects of black carbon (BC) and primary organic carbon (POC). Mike Griffin of Carnegie Mellon University (CMU) discussed the importance of uncertainty in LCA studies; Chris Malins (ICCT) presented realistic global yield estimates for energy crops; and Matt Langholtz of Oak Ridge National Laboratory (ORNL) discussed updated assessments of biomass resource potential in the U.S.

Mark Staples (MIT) discussed the pros and cons of different co-product allocation schemes for use in LCA of alternative jet fuels. This effort is driven by the International Civil Aviation Organization (ICAO), which has set a goal of carbon neutral growth for international aviation beyond the year 2020. This goal is expected to be achieved through a combination of measures, one of which is utilization of alternative fuels. LCA methodologies are being examined to provide a reliable method for quantifying GHG emissions reduction benefits from use of alternative jet fuels. One important aspect of such LCA approaches is defining appropriate methods for co-product allocation – that is, how much GHG emissions should be attributed to alternative jet fuels, and how much should be attributed to other products that are produced during the same production process.

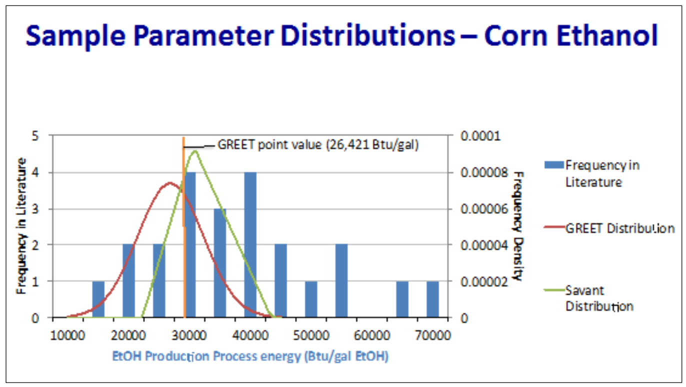
Three selection criteria were defined to evaluate the suitability of different co-product allocation methods: (1) scientifically justifiable, (2) robust to limit "gaming," and (3) implementable. Four different attributional co-product allocation options are being evaluated. The first, allocation by mass or volume of the co-products, was eliminated because it does not make intuitive sense and would be difficult to implement in systems that have a large number of diverse co-products, including electricity. The displacement (or system expansion) allocation method is more attractive, as it is already being used for some biofuels in other regulatory systems. However, this method was rejected here because it requires considerable knowledge of many co-products and their life-cycles, there is considerable spatial and temporal variation in the co-product allocation results, and there are complications with respect to displacing average vs. marginal product units. The remaining two allocation methods, revenue-based and energy-based, both meet the ICAO's selection criteria. However, revenue-based methods result in higher temporal variation in co-product allocation as compared to energy-based methods. This was illustrated using two biofuel examples: (1) jet fuel produced from soybean hydroprocessed esters and fatty acids (HEFA) and (2) soybean-based biodiesel. While a final decision has not yet been made, it is likely that an energy-based co-product allocation will be adopted for use by ICAO.

Hao Cai (ANL) discussed work being done by ANL to assess the impacts of life cycle black carbon (BC) and primary organic carbon (POC) on the potential climate effects of biofuels. Both BC and POC are short-lived climate forcers, with BC having an extremely strong global warming potential (GWP) and POC having a small cooling effect. The GREET model was expanded to include BC and POC emissions in the life cycle of several biofuel pathways. These emissions arise primarily from diesel combustion and biomass combustion at various stages throughout the life cycle. In all cases, these additions increased the calculated well-to-wheels GHG emissions associated with the biofuels. As shown in the figure, this increase was less than 5% for corn ethanol, but as high as 30% for sugarcane-derived ethanol. This much larger effect for the sugarcane pathway is a consequence of open field burning, which greatly increases BC emissions.



ANL is also investigating the potential climate effects of albedo changes resulting from biofuel-induced LUC. Albedo changes are thought to be especially important in locations that have significant snow cover (such as the Upper U.S. Midwest). Albedo data over the Midwest were obtained by MODIS satellite imagery. These data were paired with high spatial resolution cropland data layer (CDL) information from USDA. The climate effects of the albedo dynamics were estimated for different cropland types using a Monte Carlo Aerosol Cloud and Radiation (MACR) model. A variety of biofuel LUC scenarios were then examined to estimate how the resulting albedo effect would impact the life cycle global warming potential of the biofuel. Preliminary results suggest that land conversion from forest to cropland has a beneficial albedo-induced global cooling effect. However, these albedo effects are highly variable among different scenarios, and further work is necessary to improve our understanding of these effects.

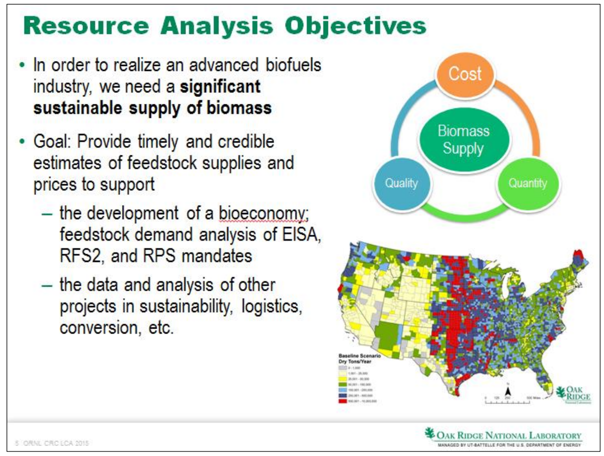
Mike Griffen (Carnegie Mellon University) described a study to assess the role of uncertainty in key LCA input parameters upon estimated GHG emissions from corn ethanol and biodiesel. The modeling framework used was the GREET-2014 model. For the corn ethanol life cycle, six key parameters were investigated: (1) corn farming energy, (2) application rate of N fertilizer, (3) N_2O emission rate, (4) ethanol production process energy, (5) process yield, and (6) LUC. For each parameter, a distribution of values was developed, based upon a review of literature information. An example of the distributions for ethanol production process energy is shown in the figure. Having such distributions for all key parameters, a Monte Carlo process was used to determine ranges of overall GHG emissions. For corn ethanol, uncertainties in the N_2O emission rate and LUC dominated the overall life cycle GHG emissions.



The same process was used to evaluate uncertainties in the soy biodiesel life cycle. In this case, seven key parameters were investigated: (1) soybean farming energy use, (2) application rate of N fertilizer, (3) N_2O emission rate, (4) biodiesel process energy, (5) process yield, (6) LUC, and (7) co-product yield. As with corn ethanol, uncertainties in N_2O emissions and LUC strongly influenced the overall uncertainty. In addition, biodiesel process energy significantly influenced the overall uncertainty. It was also pointed out that the choice of co-product allocation has an important effect upon the final estimated life cycle GHG impacts of these biofuels.

Chris Malins (ICCT) summarized a recent review undertaken by ICCT to assess realistic global yields of five energy crops: miscanthus, switchgrass, willow, poplar, and eucalyptus. Each crop was evaluated with respect to three criteria: (1) current yields, (2) improvement potential, and (3) environmental concerns. This study concluded that in most cases, expected future commercial yields will be at least 1/3 lower than yields projected from current, small-scale trials. This is because large-scale operations will likely involve growth on marginal lands that have poorer soil, less water, and less nutrients than small-scale test plots. There are numerous challenges to improving yields of most energy crops, including long breeding cycles, little response to fertilizer, and limitations of breeding mechanisms. The environmental impacts of these energy crops present a mixed bag, with some improving soil organic content (SOC) and biodiversity, but others requiring substantial amounts of water and having invasive potential. Malins suggested that policy safeguards are needed to limit energy crop growth to non-agricultural land, ensure sustainability, and protect land ecosystems. He also mentioned three implications of these lower-than-expected yields: (1) energy crop production will be more expensive than previously thought, (2) GHG benefits will be reduced, and (3) total global biomass production potential is reduced.

Matt Langholtz (Oak Ridge National Laboratory; ORNL) discussed the work of ORNL and partner organizations in assessing biomass resource potential in the U.S. As shown in the figure, the goal is to provide timely and credible estimates of biomass feedstock supplies, prices, and impacts. The first major output of this effort was the 2005 "Billion Ton Study" (BTS), which identified the potential to produce approximately 1 billion ton of dry biomass annually within the U.S. This amount was thought adequate to displace 30% of the country's petroleum consumption. This report was updated in 2011, with a focus on economic availability of feedstocks over a 20-year period. Results of this Billion Ton update (BT2) study indicated that with a biomass cost of $60/ton in 2030, sufficient feedstock could be available to satisfy nearly three times the EISA fuel requirements of 36 bg/y.



In the 2016 Billion Ton update now underway (BT16), several improvements are being made, including the following: (1) updated yields for energy crops and residues are being utilized, (2) several additional crops (including algae) are being incorporated, (3) feedstock costs will be extended beyond the farm gate to the biorefinery gate, (4) interactive display tools will enable visualization of biomass supplies, costs, and spatial distributions, and (5) the environmental effects of selected scenarios will be included. Using a variety of existing environmental models, six indicators will be used to assess the sustainability of these scenarios: air quality, water quality/quantity, soil quality, productivity, GHG emissions, and biological diversity. The BT16 report will be released in two volumes: Volume 1 (focusing on resource assessments) in July of 2016 and Volume 2 (focusing on environmental sustainability) in September of 2016.

Session 3: Advances Biofuels Modeling: LUC and Advanced Biofuels

Chairpersons: Geoff Cooper (RFA), Robb De Kleine (Ford), Luisa Marelli (JRC), and Laura Verduzco (Chevron)

Session 3 focused on the topic of LUC modeling, and recent improvements in data sets and model structures by researchers in Europe and North America. The session began with Wally Tyner of Purdue University presenting recent changes in the GTAP-BIO model, followed by Bruce Babcock of Iowa State University who described observed trends in global LUC. Tyler Lark of the University of Wisconsin discussed spatially-detailed mapping of LUC in the U.S., while Hugo Valin of the International Institute for Applied Systems Analysis (IIASA) described on-going efforts to assess LUC impacts of biofuels in the EU. Steffen Mueller of the University of Illinois-Chicago presented work investigating the relationships between LUC and soil organic carbon (SOC). Luisa Marelli of EC's Joint Research Centre (JRC) concluded the session by describing enhanced attributional LCA (ALCA) methods to assess GHG emissions resulting from use of biofuels in the EU.

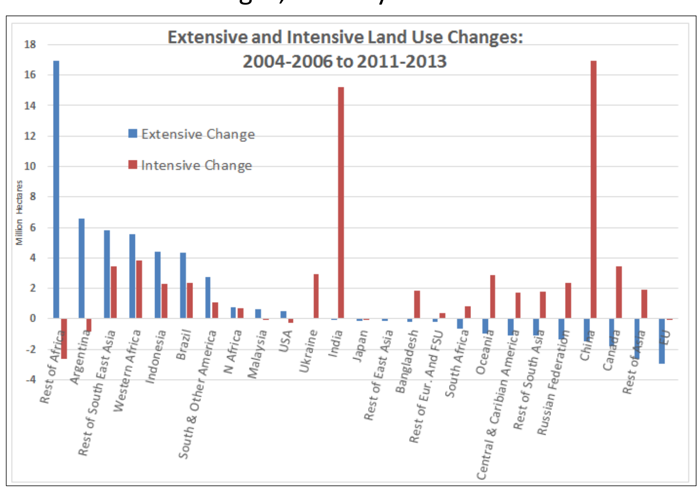
Wally Tyner (Purdue Univ.) described updates to the computable general equilibrium (CGE) model called GTAP (Global Trade and Analysis Project), and creation of a new GTAP-BIO database for assessing ILUC due to biofuels. A 2004 version of GTAP was used by CARB in determining the original CI values for biofuels under their LCFS regulations. Since that time, numerous significant global changes have occurred with respect to population, GDP, consumption, investment, and amounts of biofuels produced. These and other updates have now been incorporated into a 2011 GTAP model. An updated GTAP-BIO database has also been prepared to reflect the much larger biofuels sector in 2011 as compared to 2004, as well as several other improvements. To examine the overall effects of these model and database updates, backcast and forecast simulations were conducted and compared. For backcasting, the new 2011 GTAP model and database were used to simulate a reduction of corn ethanol by 10.5 bg/y – which represents the difference in ethanol production between 2004 and 2011. For forecasting, the 2004 model and database were used to simulate an increase of 10.5 bg/y corn ethanol. The results showed reasonably good agreement in terms of predicted ILUC and accompanying GHG impact: 14.5 g CO_{2eq}/MJ from backcasting; 13.1 g CO_{2eq}/MJ from forecasting. However, several other issues/metrics remain to be investigated.

Tyner also described sensitivity analyses being conducted to investigate the influence of four parameters upon CARB's calculated ILUC values:

1. YDEL – the yield price elasticity
2. ETA – the productivity of land converted to cropland compared to cropland productivity
3. PAEL – the elasticity that drives the increase in yield on cropland pasture as the rent for the land increases
4. Armington elasticity – a measure of the degree of substitution between home country and imported goods

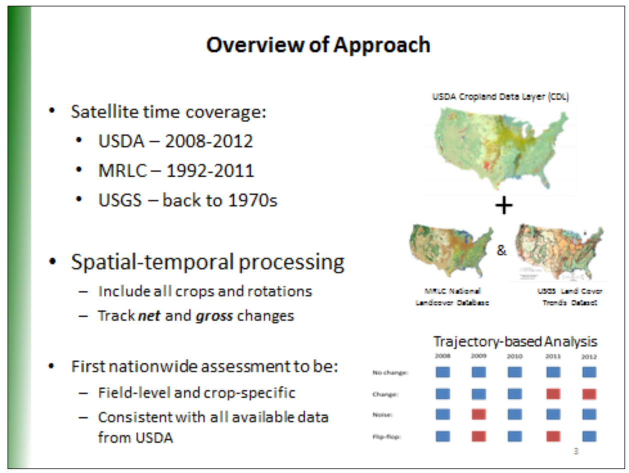
CARB ran 30 corn ethanol simulations in which they varied YDEL, ETA, and PAEL; then chose the average result (19.8 g CO_{2eq}/MJ) as the ILUC value for corn ethanol. From Tyner's analysis, it appears that CARB's approach of handling sensitivity for YDEL and ETA may slightly over-estimate calculated ILUC emissions.

Bruce Babcock (Iowa State University) discussed global LUC that has been observed over the past decade, and how this relates to economic models used to predict LUC. With large increases in global commodity prices since the mid-2000's, this has been a period of large, sustained increases in agricultural production. To investigate the details of these changes, country-level data from the U.N. Food and Agricultural Organization (FAO) were examined over two time periods: 2004-2006 and 2011-2013. Different measures of land use are important to consider. For example, the category of "harvested land" counts double-cropped land twice but does not count fallow land, whereas total cropland includes fallow land and only counts double-cropped land once. It is also important to distinguish LUC involving intensification from that involving extensification. The figure shown here



illustrates the extent of LUC (million ha) through both intensification and extensification between 2004-2006 and 2011-2013 in many countries/regions of the world. Babcock pointed out that countries exhibiting significant extensification (Brazil, Indonesia, SE Asia, and Africa) have available frontier land to support LUC. Those countries that exhibit significant intensification (India, China, SE Asia, parts of Africa) have growing populations and limited (or no) frontier land. Interestingly, very little LUC (either intensification or extensification) occurred in the U.S. or Europe over this period. Babcock concluded that in addition to global economic factors, national/regional land use policies and other socioeconomic factors are significant determinants of LUC.

Tyler Lark (University of Wisconsin-Madison) described efforts to quantify cropland conversion in the U.S. over the time period of 2008-2012. The approach used is summarized in the figure. Recent satellite data from USDA's Cropland Data Layer (CDL), combined with older satellite information from USGS is processed using trajectory-based land change algorithms to identify crop-specific LUC at fine spatial resolution over the entire contiguous U.S. The accuracy of specific LUC patterns was determined in certain areas using aerial photography from the National Agricultural Imaging Program (NAIP). This showed that the processing algorithms dramatically improved the accuracy of cropland vs. non-cropland discrimination, as well as identification of the crop type as compared to original CDL data.



Results of this analysis revealed that over the period of 2008-2012, 7.3 million acres of crop expansion occurred, but this was offset by 4.3 million acres of cropland abandonment, leaving a net increase of 3.0 million acres of cropland. New croplands originated mainly from grassland (77%), where the definition of grassland included retired cropland planted to vegetative cover. 27% of the converted grassland was observed to have been unimproved grassland for over 20 years. Conversion from grassland was widespread throughout the central part of the U.S., while conversion from wetlands was concentrated in Minnesota and the Dakotas. The most common "break-out" crop was corn, followed by wheat and soybeans. A significant fraction (42%) of the new cropland came from Conservation Reserve Program (CRP) lands. During the study period, 8.8 million acres left CRP, while 3.7 million acres were newly enrolled in CRP, leaving an overall decline of 5.1 million CRP acres. Using literature values of GHG emissions from conversion of grasslands to crops, Lark estimated the cumulative emissions from five years of LUC to be 131 million tonnes CO_2eq.

Hugo Valin (IIASA) discussed a collaborative program to assess ILUC impacts of fuels used in the EU. This is a follow-up to the MIRAGE-Biof study conducted earlier by the International Food Policy Research Institute (IFPRI). A partial equilibrium model called Global Biomass Optimization Model (GLOBIOM) is used to quantify ILUC and its impacts. GLOBIOM includes agriculture, wood, and bioenergy markets on a 50x50 km grid scale across the 28 EU Member States and 25 world regions. Through an interactive stakeholder consultation process, many areas of model improvement were identified and addressed. Valin described four specific improvements that were significant: (1) modeling of agricultural residue removal, (2) GHG emission factors for palm plantations, (3) representation of biofuel co-products, and (4) representation of multi-cropping. Numerous EU scenarios are being modeled – including investigations of many different feedstocks, different policy scenarios, and more explorative scenarios. For each scenario, a distribution of impacts is determined across a range of demand, co-product, and yield parameters. In addition, sensitivity analyses are being performed to determine how the results of LUC and GHG impacts vary with specific inputs. Results are also being compared with previous estimates for the EU and other regions. While much of this modeling work has been completed, no results were presented because they have not yet been vetted to the project stakeholders.

Steffen Mueller (University of Illinois-Chicago, UIC) discussed recent work by UIC and ANL to improve understanding of LUC and its impact on soil organic content (SOC) and GHG emissions. Advancements in remote sensing data tools have enabled more reliable determinations of LUC on specific parcels of land. For example, use of the Genscape/GRAS tool enables side-by-side viewing of aerial images from the USDA NAIP database. This provided for much faster and more accurate assessment of LUC in the U.S. For international LUC analysis, the Genscape/GRAS tools are used with MODIS satellite imagery.

Advances in understanding carbon stocks are being made by developing and applying an improved Carbon Calculator for Land Use change for Biofuel (CCLUB) model that is used with GREET. An SOC model based on the CENTURY agroecosystem model is used as a foundation. Multiple feedstocks are considered, along with various options such as different tillage systems and different GTAP land area scenarios. Importantly, various land management change (LMC) scenarios for stover-based ethanol production are included – such as different stover removal rates, and carbon adjustments from use of cover crops and application of manure.

Use of the new CCLUB model with higher spatial resolution shows that conversion of cropland or cropland-pasture (C-P) to corn generally increases SOC, while conversion of grassland or forest to corn generally decreases SOC. Conversion of all land types to energy grasses (switchgrass and miscanthus) increased or maintained SOC, while conversion to short rotation woody crops (poplar and willow) decreased SOC. Mueller also discussed the importance of understanding and properly classifying carbon content of C-P lands. Use of the CCLUB model requires an understanding of land use history. It is assumed that during periods of C-P increase, carbon content is more characteristic of pastureland, while during periods of C-P decrease (such as the current period) carbon content is more characteristic of cropland. It is also important to consider proper spatial resolution and use of appropriate baselines for comparison.

Luisa Marelli (JRC) described approaches being used to enhance attributional LCA (ALCA) to assess GHG emissions and their impacts from use of biofuels and bioenergy in the EU. This work is being done to support achievement of the 2020 RED targets, as well as to investigate post-2020 GHG reductions. The emphasis is on utilization of wastes and residues to produce biofuels and bioenergy, as such feedstocks do not compete with food and land, and they introduce no ILUC emissions. However, different feedstocks and scenarios have different environmental impacts, which can be evaluated using an "advanced" approach to ALCA. Marelli explained how consequential thinking and advanced tools can be applied to ALCA studies to enable comparison of potential environmental risks from different bioenergy and fossil-based systems. This is done by expanding the system boundaries beyond the traditional "supply-chain" approach used with ALCA to include carbon pools in agricultural and forest systems. In addition, besides the impacts of well-mixed GHGs (WMGHG), near-term climate forcers (NTCF) such as NOx, CO, NMVOC, BC, and OC were included.

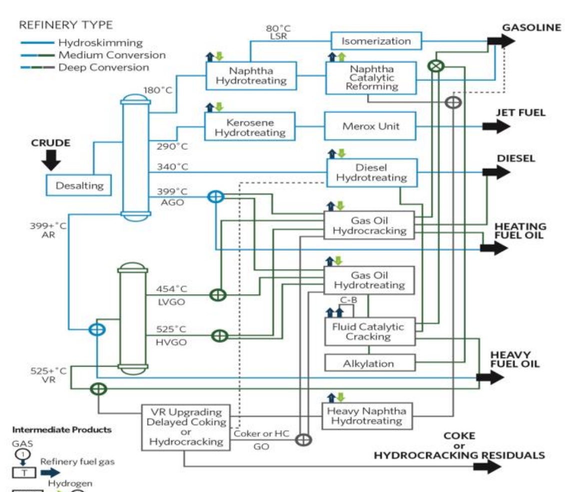
Numerous modeling scenarios and biomass pathways are being explored, and sensitivity analyses (stress tests) are being performed to understand the robustness of the modeling results under a range of different input assumptions. Three categories of pathways are being analyzed: power generation, heat, and biofuels. Model results are expressed in terms of absolute global temperature change potential (AGTP) through year 2100, using IPCC methodologies. Results showed that all bioenergy pathways considered produced smaller temperature increases than the fossil-fuel baseline, with some pathways providing greater benefits than others. It was also shown that both WMGHG and NTCF are important, and that including land use and carbon stocks in the ALCA approach is critical. Finally, several additional environmental impacts were assessed (eutrophication, PM emissions, biodiversity, photochemical ozone formation, etc.). In most cases, more adverse impacts were found for the bioenergy systems compared to the fossil energy baseline.

Session 4: Advances in LCA of Petroleum/Alternatives

Chairpersons: Jeff Farenback-Brateman (ExxonMobil), Amit Kapur (Phillips66), and Devin O'Grady (Natural Resources Canada)

Session 4 consisted of five presentations focused on LCA assessments and data needs for petroleum-derived fuels and other non-biofuel alternatives. Joule Bergerson of the University of Calgary described a petroleum refinery model used to assess the impacts of crude oil quality and refinery configurations on GHG emissions. Raymond Speth of MIT discussed a global LCA study to determine well-to-pump (WTP) GHG emissions for petroleum fuels produced around the world. Michael Wang of ANL discussed the potential GHG benefits of high octane fuels (HOFs) in the U.S., while Jim Anderson of Ford discussed economics and GHG benefits of similar HOFs when used in the U.S. light-duty vehicle fleet. This session closed with a second presentation by Raymond Speth, who also discussed potential economic and environmental benefits of HOFs.

FIGURE 5
Refinery Configurations in PRELIM



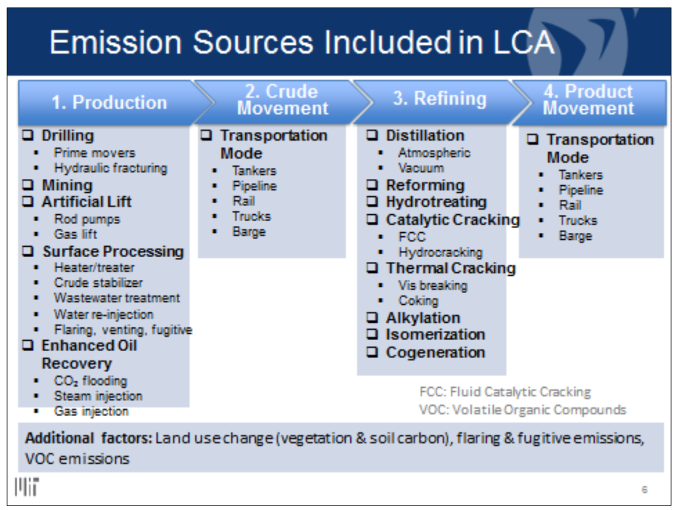
Source: Petroleum Refinery Life-Cycle Inventory Model

Note: See list of acronyms for more information.

Joule Bergerson (University of Calgary) discussed the development and use of the Petroleum Refinery Life Cycle Inventory Model (PRELIM) for investigating the impacts of crude oil quality and refinery configuration on energy use and GHG emissions. The original motivation for developing PRELIM was to assess GHG impacts of products from oil sands-derived feedstocks, but the model is now being used for many other crudes and products around the world. As shown in the figure, the refinery configuration in PRELIM is quite comprehensive, including various levels of hydrotreating/ hydrocracking. Over the past few years, much effort has been expended to evaluate and improve PRELIM. Enhancements include allowing blends of crudes, variations in refinery size, addition of more crudes to the inventory, better differentiation of product slate properties, and other improvements.

PRELIM is now being used in a Carnegie Endowment-funded project to establish an international Oil Climate Index (OCI). Life cycle GHG emissions are being determined using three open-source models: (1) Oil Production Greenhouse gas Emissions Estimator (OPGEE) for upstream emissions, (2) PRELIM for mid-stream (refinery) emissions, and (3) Open Emission Model (OPEM) for downstream (combustion) emissions. These models have been applied to 30 test crudes thus far, with 75 more crudes to be evaluated in Phase 2. The mid-stream emissions from these 30 crudes range from 20 to 100 kg CO_{2eq}/bbl, with hydrogen production/consumption within the refinery being the biggest factor differentiating emissions between crudes. Overall, crude quality and refinery configuration are the biggest drivers of mid-stream life cycle GHG emissions. More data of higher quality are needed to further improve the reliability of PRELIM.

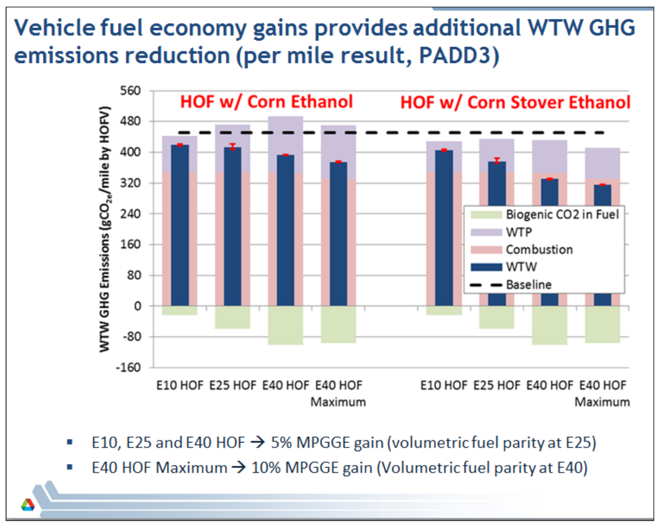
Raymond Speth (for Robert Malina; MIT) described a worldwide LCA study to determine GHG emissions associated with the production and distribution of transportation fuels from petroleum. This analysis was performed retrospectively for 2005 and 2012, and prospectively for 2020. The spatial domain included 8 world regions (N. America, Central and S. America, Europe, Asia, Middle East, Africa, Oceania, and Former Soviet Union). The oil supply chain was examined to determine well-to-pump (WTP) GHG emissions. The approach used included data collection from numerous sources, estimation of values for missing data, categorization of similar units/processes, aggregation of data at country-specific level, and assessment of uncertainties. The emission sources included in the LCA are summarized in the figure. In total, 72 sources of emissions associated with crude production in 90 countries were used, along with 687 refineries in 112 countries.



Refinery emissions were estimated for each process unit, with these emissions being allocated to the final fuel products in proportion to ultimate use of the product streams. Total GHG emissions were determined for each finished fuel, based on the location of fuel consumption. WTP emissions varied regionally depending upon various factors, but especially the degree of refinery complexity, which was expressed as the ratio of secondary processes to distillation volumes. Refineries in N. America have the highest complexity, while those in Africa have the lowest. Preliminary results indicate global mean WTP emissions for gasoline, diesel, jet fuel, and bunker fuel to be 22.5, 18.7, 14.8, and 13.0 g CO_2eq/MJ, respectively. The different values among these fuels are mainly due to differences in the extent of catalytic cracking, hydrocracking, and hydrotreating that are employed to produce them. On a regional basis, WTP emissions of average refinery products are highest in N. America and lowest in the Middle East (approximately 22 vs. 12 g CO_2eq/MJ). Globally, WTP emissions of all fuels increased about 4% between 2005 and 2012, and are expected to increase by another 4% by 2020. This increase is largely driven by greater use of unconventional petroleum resources, though it is partially offset by reduced flaring activities. Work is underway to develop projections for 2050.

Michael Wang (ANL) discussed the well-to-wheels (WTW) analysis of a larger DOE-funded effort involving ANL, Oak Ridge National Laboratory (ORNL) and the National Renewable Energy Laboratory (NREL) to investigate the potential of producing and using high octane fuel (HOF) in light-duty vehicles throughout the U.S. HOF was defined to have a Research Octane Number (RON) of 100, as compared to today's E10 baseline gasoline with a typical RON of about 92. In this modeling study, higher levels of ethanol are blended with refinery-produced Blendstocks for Oxygenate Blending (BOB) to produce the HOFs. Refinery linear program (LP) modeling was conducted to determine the energy use and GHG emissions associated with producing HOFs consisting of E10, E25, and E40. Refineries in two Petroleum Administration Defense Districts (PADD2 and PADD3) were modeled, using three different refinery configurations, characterized as cracking, light coking, and heavy coking. The crude slates for these refineries were taken from the U.S. Energy Information Administration's Annual Energy Outlook (EIA-AEO) projections for 2020. Market penetration of the HOFs was modeled from 3% to 71% of the gasoline market.

The GREET model was used to assess overall WTW GHG emissions of various HOF scenarios. Results showed that refinery emissions changed very little when producing BOBs for E10 to E40 fuels. However, GHG emissions were reduced substantially with increasing ethanol blend level. Also, larger GHG emissions reductions were modeled when assuming use of ethanol derived from corn stover as compared to corn starch. In addition, vehicle efficiency improvements of 5% and 10% were assumed when using HOFs. These efficiency gains produced additional GHG reductions credited to the HOFs. The life-cycle GHG results, expressed as g CO_{2eq}/mile, are summarized in the figure. Wang concluded that the sum of vehicle efficiency gain and high ethanol blending results in significant GHG reductions when using HOFs.



Jim Anderson (Ford) discussed a USCAR study to assess the costs and GHG benefits of high octane fuels (HOF) in light-duty vehicles. This interest is driven by the need to significantly improve fuel economy of the vehicle fleet over the next decade. Use of HOF enables high engine efficiency, and thus lowers GHG emissions, but producing HOF may increase refinery emissions. This study investigated the optimum vehicle/fuel combinations to maximize reduction of well-to-wheels (WTW) GHG emissions. While there have been several other WTW studies to analyze the effect of gasoline octane, this study included new considerations, such as use of higher ethanol blends and incorporation of engine efficiency enhancements.

A refinery linear programming (LP) model by MathPro was used to estimate effects on the U.S. refining industry of meeting higher RON values (from 92 to 102) and blending higher ethanol fuels (E10, E20, E30, and E10+E85). Other key assumptions included the allowance of refinery investments, satisfying

EIA's fuel volume projections for 2017, and a crude oil cost of $96/bbl. The octane level of finished gasoline depends upon the RON of the refinery-produced BOB and the amount of blended ethanol. In the LP model, BOB octane was adjusted by modifying the severity of the refinery reformer unit. Modeling results indicated that CO_2 emissions would increase 1-2% if HOFs were produced using ethanol-BOB blends (95 RON with E10, 98 RON with E20 and E30). These fuels would also have increased cost of about 3-8 cents/gge.

Engine efficiency modeling was performed to investigate the effects of increased octane and increased compression ratio (CR), and to estimate the resulting changes in CO_2 emissions. The largest CO_2 reduction benefits resulted from use of HOF in optimized engines (having higher CR). Combining the results of the refinery and engine modeling, Anderson concluded that use of HOF in optimized engines creates a "triple win" of reduced WTW GHG emissions, reduced consumption of petroleum, and reduced WTW cost to the consumer (assuming the higher fuel costs are offset by savings from higher efficiency vehicles).

Raymond Speth (MIT) discussed a modeling study that explored the potential environmental and economic benefits of producing and using high octane (HO) gasoline in the U.S. LDV fleet. The objective was to identify the HO situation that maximizes overall societal benefit with respect to costs and GHG impacts. Currently, gasoline anti-knock index (AKI) is determined using a combination of Research Octane Number (RON) and Motor Octane Number (MON). However, as engine design has evolved, RON has become a far better indicator of knock resistance in actual operation. Therefore, Speth argued that RON alone should be used in place of the traditional AKI value, and that this change would enable the benefits of HO gasoline to be more easily realized. An increase of 4-6 RON above today's typical levels would enable a compression ratio (CR) increase of about 1 number, thereby providing improved engine efficiency and reduced fuel consumption (and GHG emissions). However, producing such HO fuels requires additional refinery processing, which increases GHG emissions.

The modeling scenario investigated assumed production of a 98 RON premium grade gasoline, along with a 92 RON regular grade – both containing 10% ethanol. Between 2020 and 2040, the LDV fleet would transition from a Regular/Premium ratio of 90:10 to 20:80. A linear programming (LP) refinery model was used to determine the optimum configuration to produce these products at maximum profit. A well-to-wheels (WTW) analysis was conducted to assess the CO_2 emissions in 2040. Results indicated that CO_2 reductions from use of higher efficiency vehicles would exceed increased emissions from refinery changes to produce the HO fuels. In 2040, total WTW CO_2 reductions of 17-33 million tons were estimated, which represents approximately 2-4% of total LDV CO_2 emissions. The direct economic impact of these fuel changes in 2040 was estimated between savings of $5.1 billion and costs of $1.1 billion. When factoring in a $66/ton "social cost of CO_2," the economic impact becomes a total savings of $0.1-7.3 billion.

Additional sensitivity modeling cases were explored. This showed that further increasing the RON of premium gasoline from 98 to 100 increased the costs significantly, without improving CO_2 reductions. Using higher ethanol contents in the premium gasoline (E15 and E20) increased CO_2 reductions and reduced costs. Similarly, enhanced CO_2 and cost benefits resulted from advanced refinery sensitivity cases in which processing unit capacities and configurations were modified.

Biodiesel Feedstock Workshop Summary

The day prior to this CRC Workshop, the National Biodiesel Board (NBB) hosted a Biodiesel Feedstock Workshop at ANL to discuss production, market trends, sustainability, and other issues for a wide variety of biodiesel feedstocks. Don O'Connor of $(S\&T)^2$ Consultants presented highlights and outcomes of this workshop. Specific feedstocks covered included soybean oil, distillers corn oil, other recycled oils and greases, palm oil, canola oil, camelina, algae, and pennycress. For most of these feedstocks, production is increasing. One reason is interest in increased utilization of existing land through multi-cropping and reduction of fallow operations. Many of the seed crops (canola, camelina, and pennycress) can be grown in place of fallow operation during crop rotations. In some situations, this can also provide soil and ecological benefits, although these crops can be difficult to grow and harvest.

Distillers corn oil is currently produced at a rate of 2.5-3.0 billion lbs/year, but this could increase significantly with the improved extraction processes now being developed. Trap grease is also abundant (potential of 3.5 billion lbs/year), but there are significant challenges in collecting and using this feedstock for biodiesel. Palm oil is a major feedstock for biodiesel internationally, but raises significant environmental issues due to high GHG emissions if the palm is grown on drained peat soils. The State of California offers unique potential for increased production of winter oilseeds such as canola and camelina, as these crops would produce "ILUC-free" biodiesel feedstocks.

O'Connor also discussed LCA modeling challenges related to non-traditional biodiesel feedstocks. A major issue is the lack of real-world data regarding the life cycles of fuels produced from these feedstocks. One important factor is emissions of N_2O from various agricultural activities. Most oilseed crops have high nitrogen requirements relating to protein production, and high nitrogen levels in crop residues that are recycled to the soil. The effects of this with respect to N_2O emissions vary with crop type, soil type, season, soil moisture level, and other factors. Understanding these issues and their implications with respect to LCA modeling of biodiesel will require further study.

Session 5: Panel Discussion on LCA Improvements, "Look-Back" on Progress, "Look-Forward" to Future Work, and Workshop Summary

Chairperson: John DeCicco (University of Michigan); Moderator: Madhu Khanna (University of Illinois); Panelists: Luisa Marelli (JRC), Vincent Camobreco (US EPA), Robert Edwards (JRC), Jennifer Dunn (ANL), and Don O'Connor $(S\&T)^2$

Session 5 consisted of a rather free-flowing discussion on a wide variety of LCA-related topics. The Session Chair and Moderator initiated these topics with a series of probing questions, but the responses and ensuing discussion by the panelists, and other Workshop participants, wandered into many other areas. Some of the main points emerging from this discussion are summarized below. Because these summaries are meant to capture general themes and multiple points of view, no comments are specifically attributed to individual speakers.

- There was considerable discussion about the importance of knowing the purpose for which LCA approaches are to be used. For example, more sophisticated modeling methods – requiring more data-intensive inputs – are necessary to develop and analyze the impacts of regulatory policy than to monitor compliance with the policy.

- Numerous suggestions were offered regarding further improvement of LCA modeling. Some thought that climate forcing factors beyond GHGs should be included, such as black carbon (BC) and albedo effects. Others suggested that land use changes and their carbon impacts need to be better understood – especially the category of cropland-pasture and its carbon stock.
- Several participants indicated that ILUC is the area where LCA uncertainty is the greatest, and that additional work is needed to reduce this uncertainty. Some noted that the contribution of ILUC to overall carbon intensity of biofuels seems to be declining as time passes and better data are becoming available. Others disputed this, believing that while ILUC is still highly uncertain, it remains a potentially significant factor. It was also pointed out that large uncertainty does not imply no effect.
- It was mentioned that attributional LCA (ALCA) is "average focused," but that marginal effects are probably more relevant for biofuel assessments. It is important to improve our understanding of LUC impacts on a spatially-detailed basis, in locations where marginal biofuel changes are occurring.
- There was general consensus that LCA of fossil fuels is more precise than LCA of biofuels. However, there is considerable variation in different fossil fuel pathways, creating a possible problem of "moving baselines."
- In some situations, it's important to not only compare a biofuel to a petroleum fuel baseline, but also compare between different biofuels. This can be difficult due to varying levels of data quantity and quality for different biofuels. In addition, other alternative fuels – such as hydrogen, renewable natural gas, and electricity – are of interest, and have their own data limitation problems.
- Thus far, most regulatory applications of LCA modeling have been focused on 1st generation biofuels. For advanced biofuels, there are even more challenges with respect to data availability and reliability. Also, spatial heterogeneity of the biomass feedstocks, and the unique conditions in each location, are important factors.
- For regulatory purposes, LCA models have used specific biofuel volume "shocks." Some suggested that approaches for modeling gradual increases in biofuel volumes should be explored, rather than single, large shocks. Others thought the emphasis should not be placed on specific fuel volumes at all, but on the cost effectiveness of GHG reductions, or other metrics.

APPENDIX I

Glossary of Terms Used During the Workshop

AEZ-EF	Agricultural Ecological Zone – Emission Factor (model)
AGTP	Absolute Global Temperature Potential
AKI	Anti-Knock Index
ALCA	Attributional Life Cycle Assessment
ANL	Argonne National Laboratory
BBE	Bio-Based Economy
BC	Black Carbon, and British Columbia
BOB	Blendstock for Oxygenate Blending
BTS	Billion Ton Study
CARB	California Air Resources Board
CARD	Center for Agricultural and Rural Development
CCLUB	Carbon Calculator for Land Use change for Biofuels
CDL	Cropland Data Layer
CGE	Computable General-Equilibrium
CI	Carbon Intensity; also Compression Ignition
CLCA	Consequential Life Cycle Assessment
CMU	Carnegie Mellon University
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
CONCAWE	CONservation of Clean Air and Water in Europe
C-P	Cropland-Pasture
CR	Compression Ratio
CRC	Coordinating Research Council
DOE	U.S. Department of Energy
EC	European Commission
EER	Energy Efficiency Ratio
EF	Emission Factor
EIA	Energy Information Administration
EIO-LCA	Economic Input-Output- Life Cycle Assessment Model
EISA	Energy Independence and Security Act
EOR	Enhanced Oil Recovery
EPA	(US) Environmental Protection Agency
EU	European Union
EV	Electric Vehicle
FAME	Fatty Acid Methyl Ester (biodiesel)
FAO	(UN) Food and Agricultural Organization
FAPRI	The Food and Agricultural Policy Research Institute
FASOM	The Forest and Agricultural Sector Optimization Model
FQD	Fuel Quality Directive
g $CO_{2,eq}$ MJ^{-1}	grams of CO_2, equivalents per MJ of fuel

GGE	Gasoline Gallon Equivalent
GHG	Greenhouse Gas
GHGenius	LCA model used in Canada
GLOBIOM	Global Biomass Optimization Model
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GTAP	Global Trade and Analysis Project
GWP	Global Warming Potential
HANPP	Human Appropriation of Net Primary Production
HEFA	Hydroprocessed Esters and Fatty Acids
HOF	High Octane Fuel
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
ILUC	Indirect (or Induced) Land Use Change
IMAGE	Integrated Model to Assess Global Environment
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JEC	JRC, EUCAR and CONCAWE
JRC	(EC) Joint Research Centre
LCA	Life Cycle Assessment
LCAOST	Life Cycle Assessment of Oil Sands Technologies
LCFS	Low Carbon Fuel Standard
LEM	Life Cycle Emissions Model
LHV	Lower Heating Value
LMC	Land Management Change
LNG	Liquefied Natural Gas
LP	Linear Programming (refinery model)
LPG	Liquefied Petroleum Gas
LUC	Land use change
MACR	Monte Carlo Cloud and Radiation (model)
MAGNEN	Modular Applied GeNeral Equilibrium Tool
MIRAGE	Modeling International Relationships in Applied General Equilibrium
MODIS	Moderate Resolution Imaging Spectroradiometer (on satellite)
MON	Motor Octane Number
MOVES	Motor Vehicle Emission Simulator (EPA model)
N_2O	Nitrous Oxide
NAIP	National Agricultural Imaging Program
NBB	National Biodiesel Board
NPV	Net present value
NREL	National Renewable Energy Laboratory
NTCF	Near-Term Climate Forcer
OCI	Oil Climate Index

OPEM	Open Emission Model
OPGEE	Oil Production Greenhouse gas Emission Estimator
ORNL	Oak Ridge National Laboratory
PADD	Petroleum Administration for Defense District
PHEV	Plug-in Hybrid Electric Vehicle
POC	Primary Organic Carbon
PRELIM	Petroleum Refining Life Cycle Inventory Model
RED	Renewable Energy Directive
RFS	Renewable Fuels Standard
RON	Research Octane Number
SI	Spark Ignition
SOC	Soil Organic Carbon
TTW	Tank-to-Wheels
UIC	University of Illinois-Chicago
USCAR	U.S. Council for Automotive Research
USDA	U.S. Department of Agriculture
WMGHG	Well-Mixed Greenhouse Gas
WTP	Well-to-Pump
WTT	Well-to-Tank
WTW	Well-to-Wheels